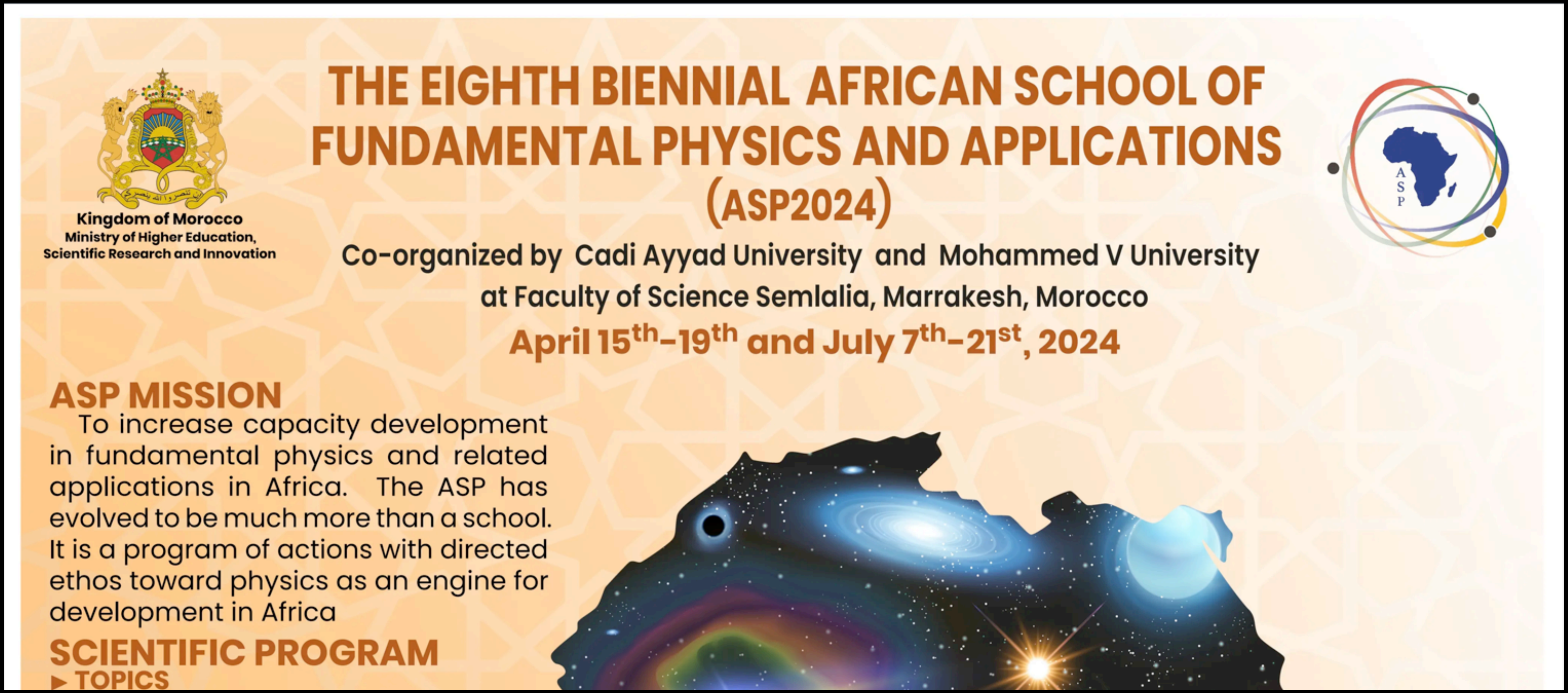
Dark Matter and Dark Sectors: Lecture 2



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Recap: lecture 1

- We have much astrophysical evidence that dark matter exists

- We do not know what it is, but we know what properties it must have and non of the SM particles fit the profile

- We know that: 1. It must be stable
  2. Non relativistic
  3. Must not interact via SM charges

- Many possibilities of what DM could be

- Very well motivated possibility called WIMP

Late 1970s - Vera Rubin

Image: Carnegie Institute for Science

$$\frac{mv^2}{r} = \frac{GMm}{r^2}$$

$$v = \sqrt{\frac{GM}{r}}$$

First scientist to measure star speeds with very high accuracy

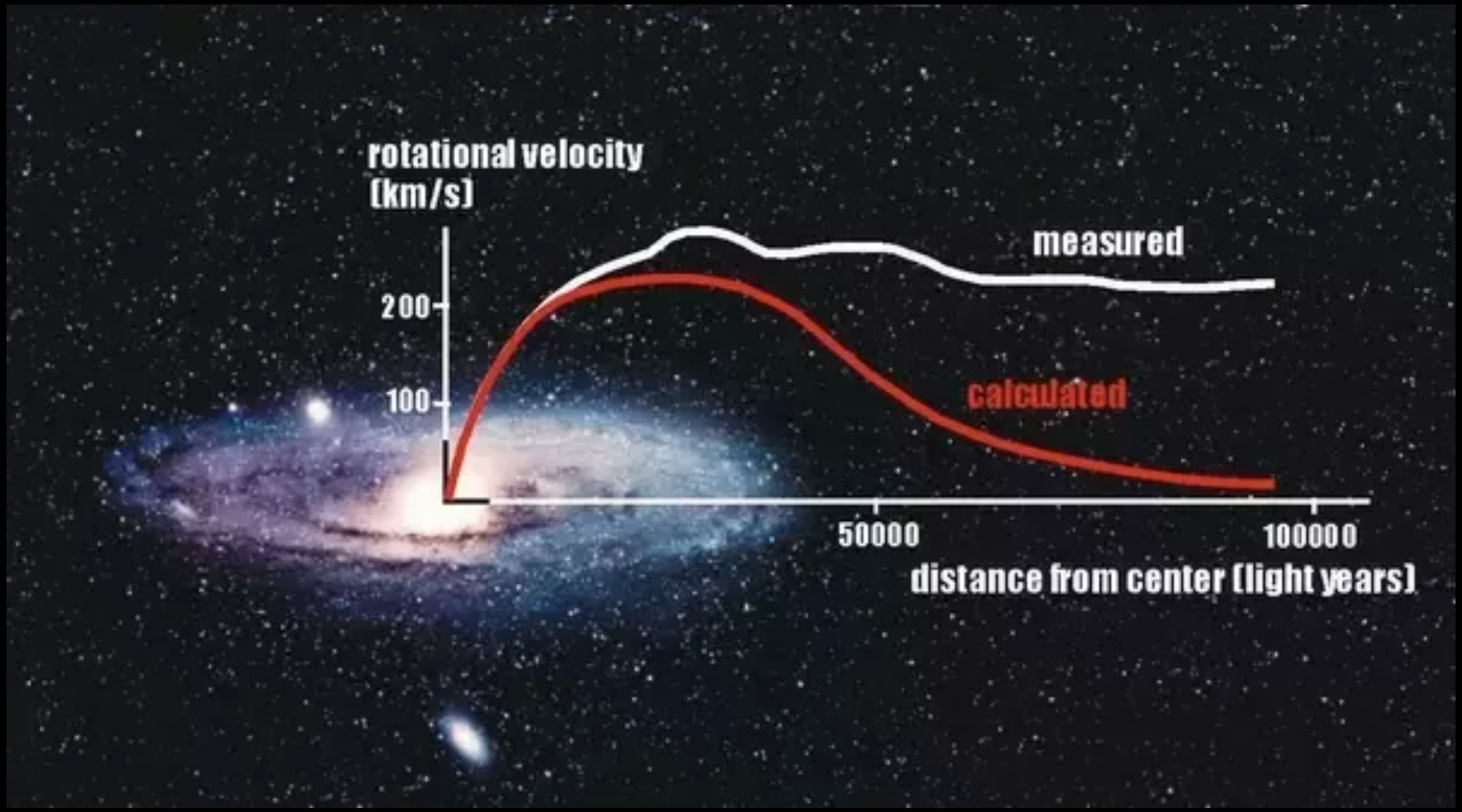
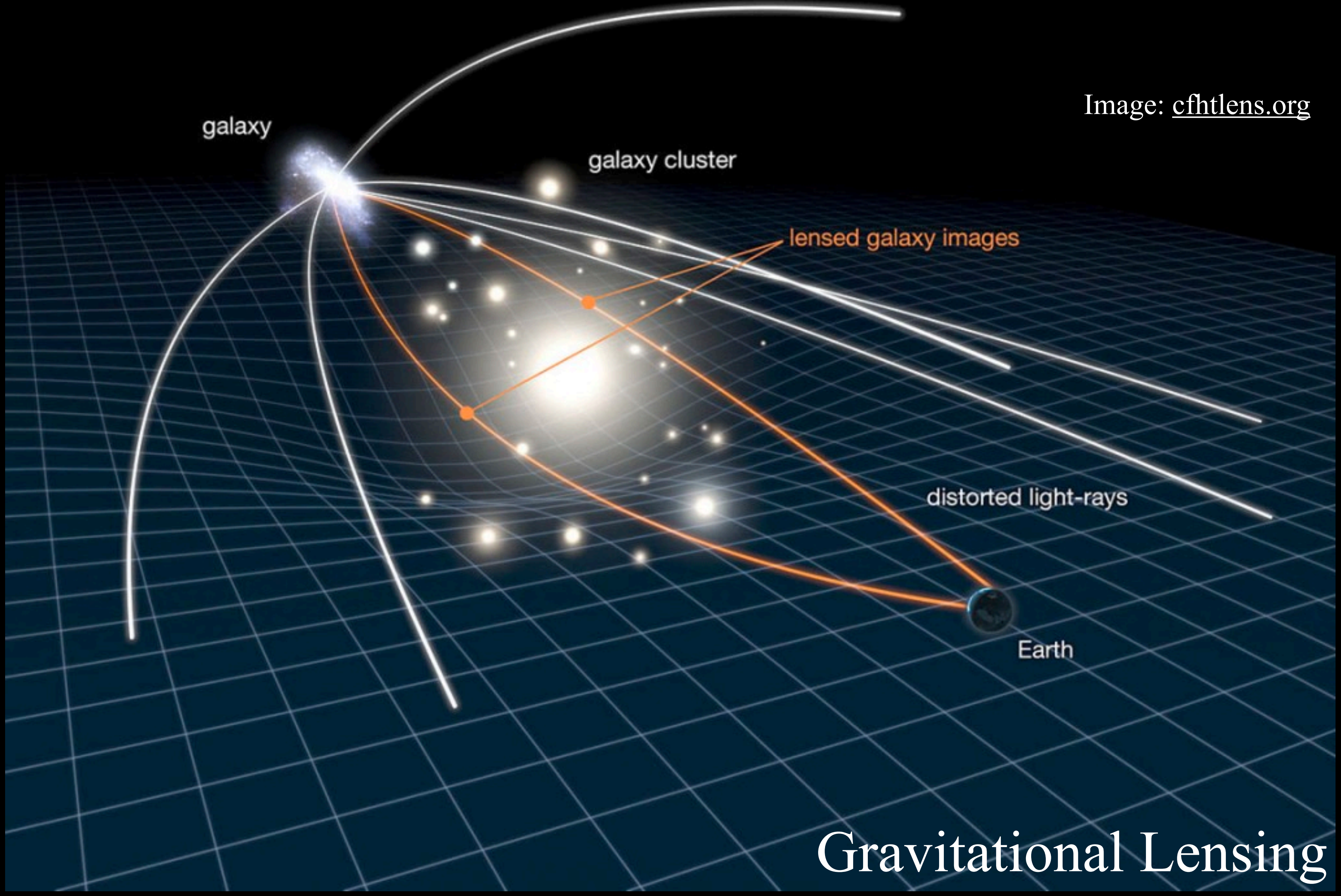


Image: quora.com

Lets look at scales larger than galaxies

Gravity can also bend light coming from distant objects



Light from galaxy is bent by gravitational field of galaxy cluster

What do galaxy clusters tell us about DM?

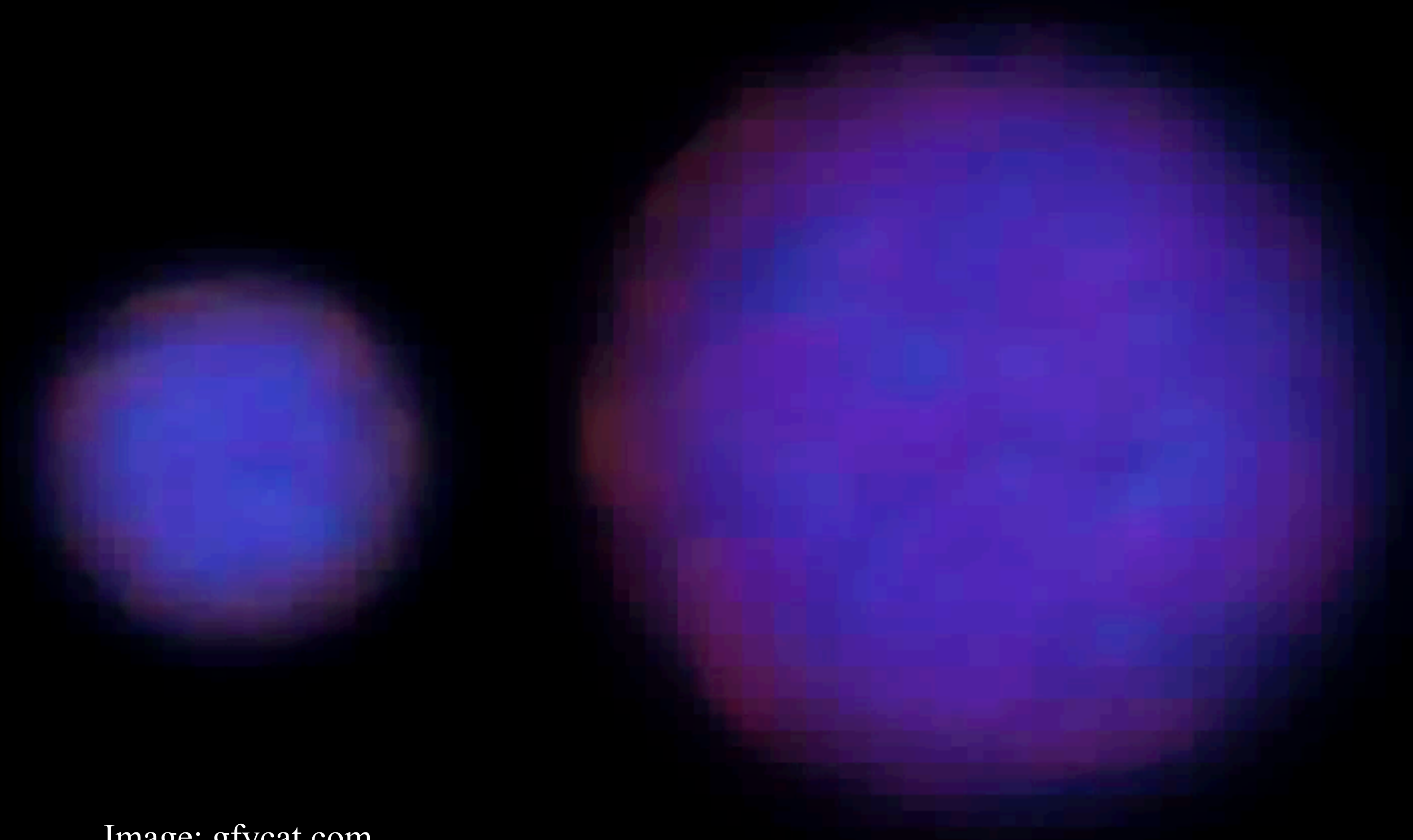


Image: gfycat.com

Visible Matter

Dark Matter

Gravitational Lens

Image: yumpu.com

What do cosmological observations tell us?

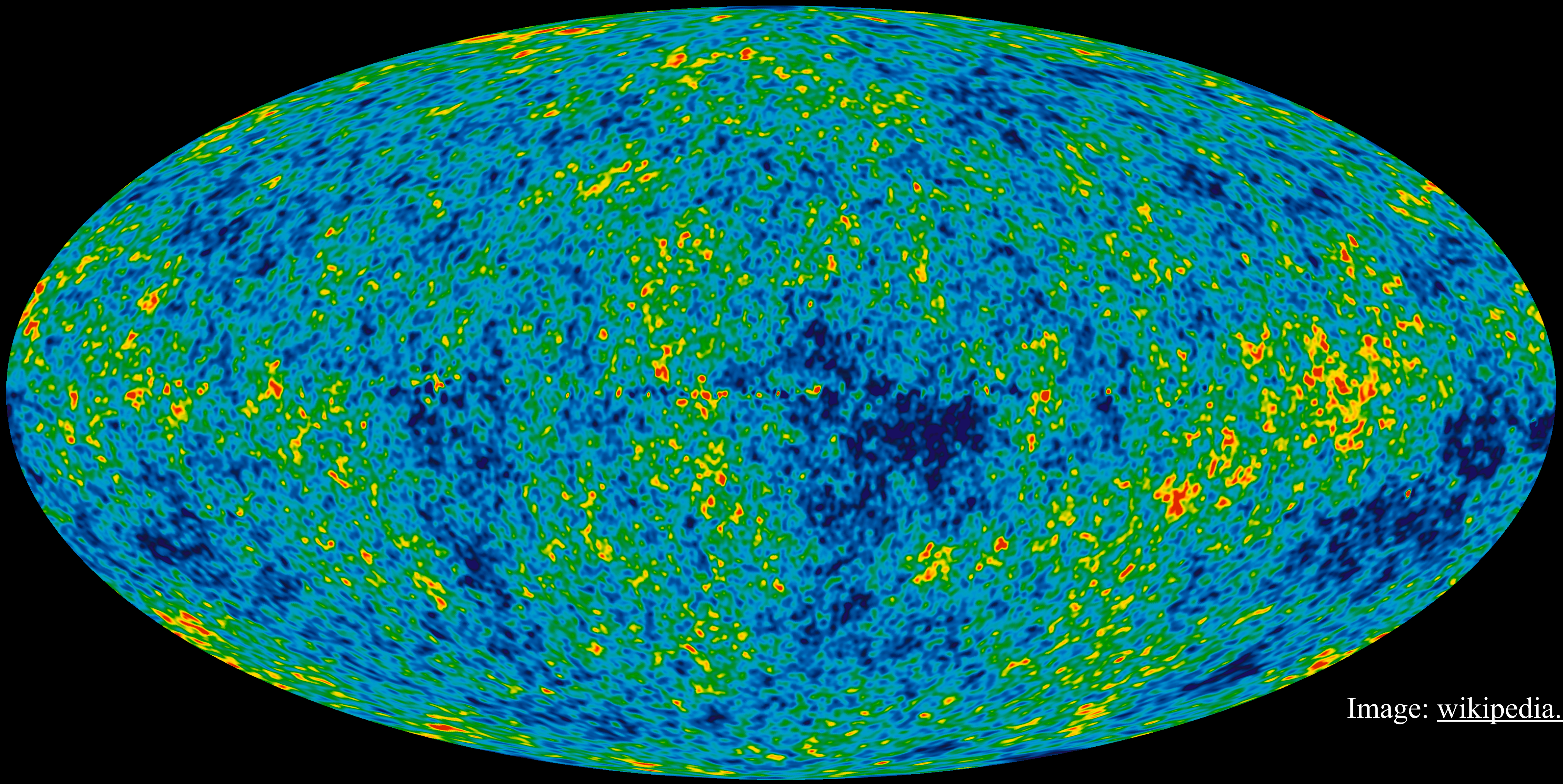


Image: wikipedia.org

Epoch of recombination

- Neutral atoms were formed, photons could move freely since they were no longer locked to charged particles

- These free moving photons reach us today

What do cosmological observations tell us?

CMB Power Spectrum -
gives cosmologists a way to mathematically understand fluctuations

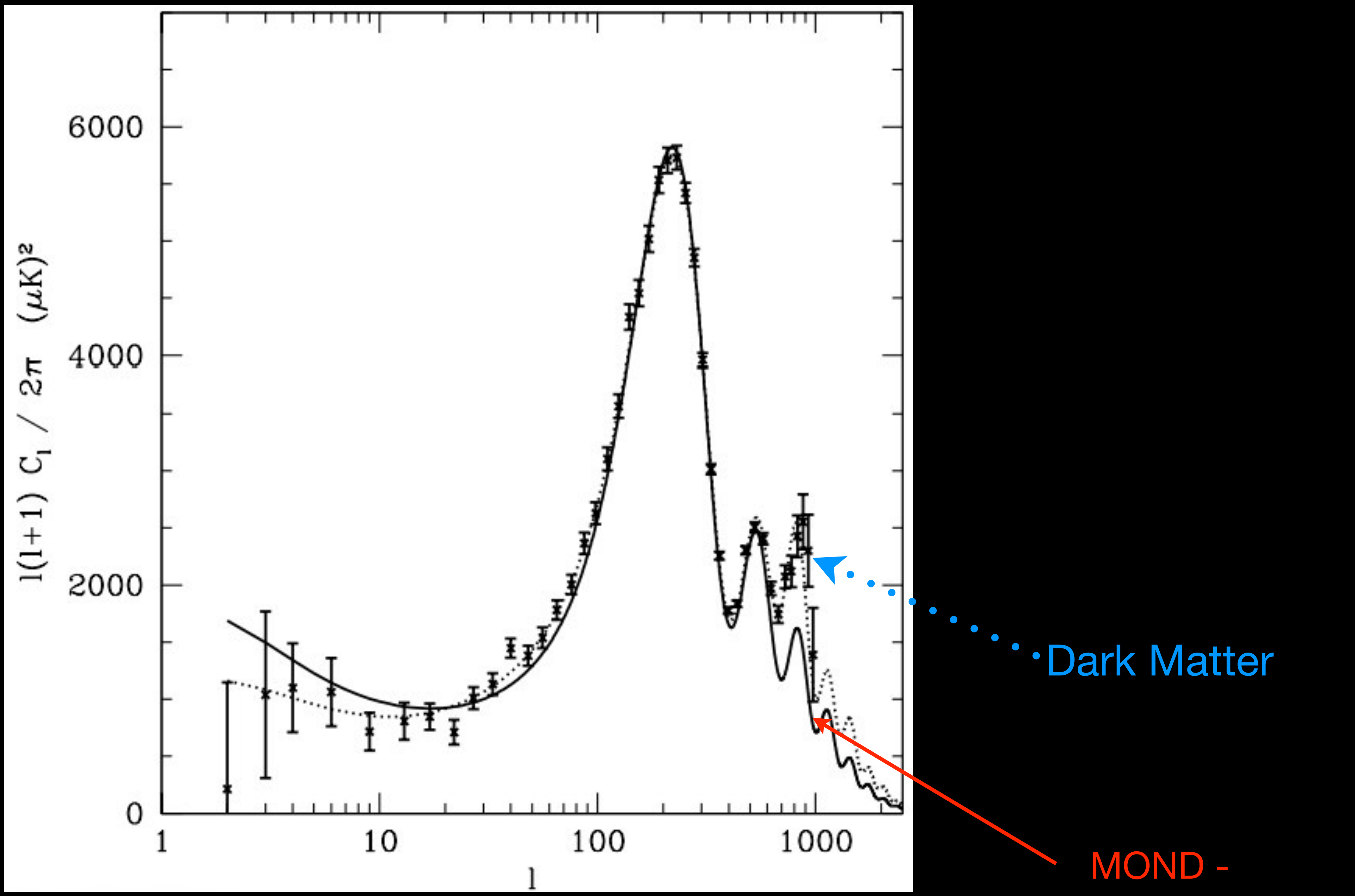


Image: Sean Carrol

Evidence shows dark matter exists at largest scales

What is Dark Matter made of?

We simply have no idea.

We DO know:

- It must be cold (non-relativistic) at the time of structure formation
- It must be super long-lived or completely stable
- It must be some new state lying beyond the SM

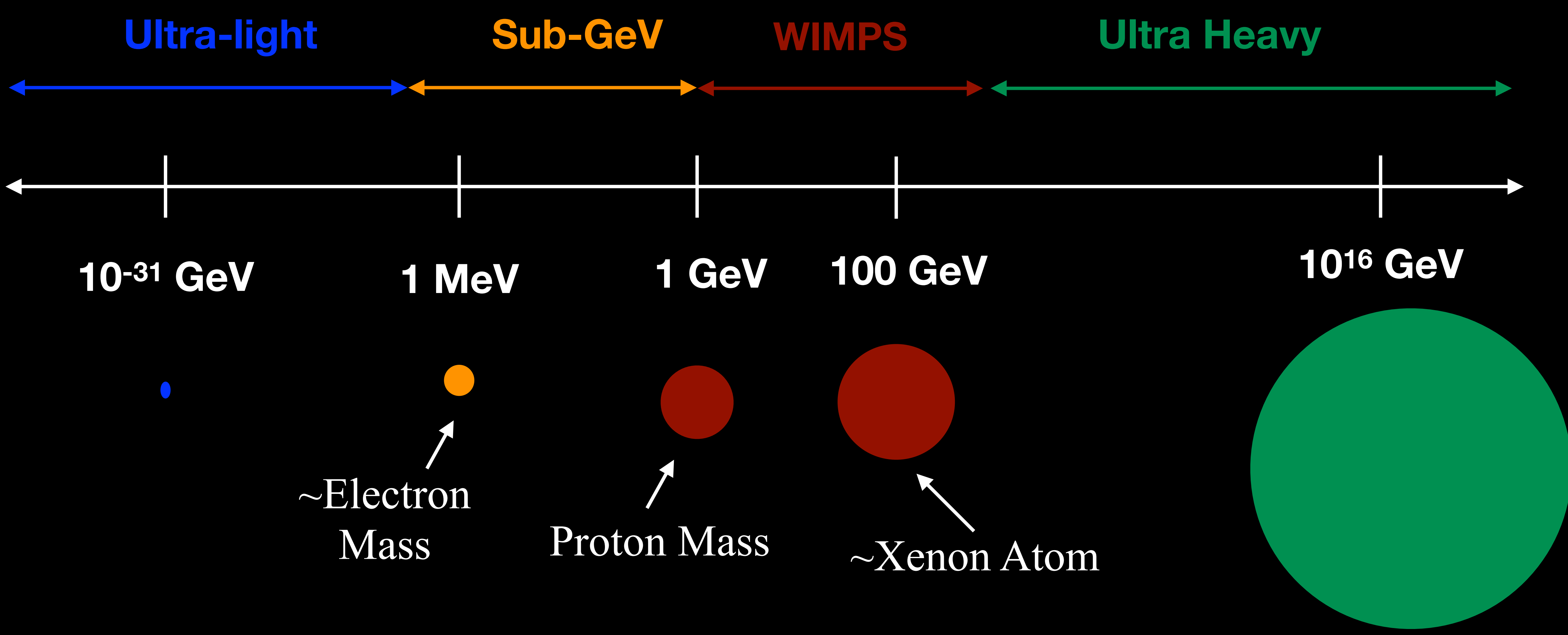
Non-EM interacting
Non-QCD interacting

Dark Matter should be described by a quantum field corresponding to a definite spin, uncharged under $U(1)_{EM}$ or $SU(3)_{C}$.

(So: no tree-level interactions with gluons or photons).

- It **may** interact with the SM through some new force

Range of possibilities is VAST



Primordial Blackholes - much heavier than Ultra heavy

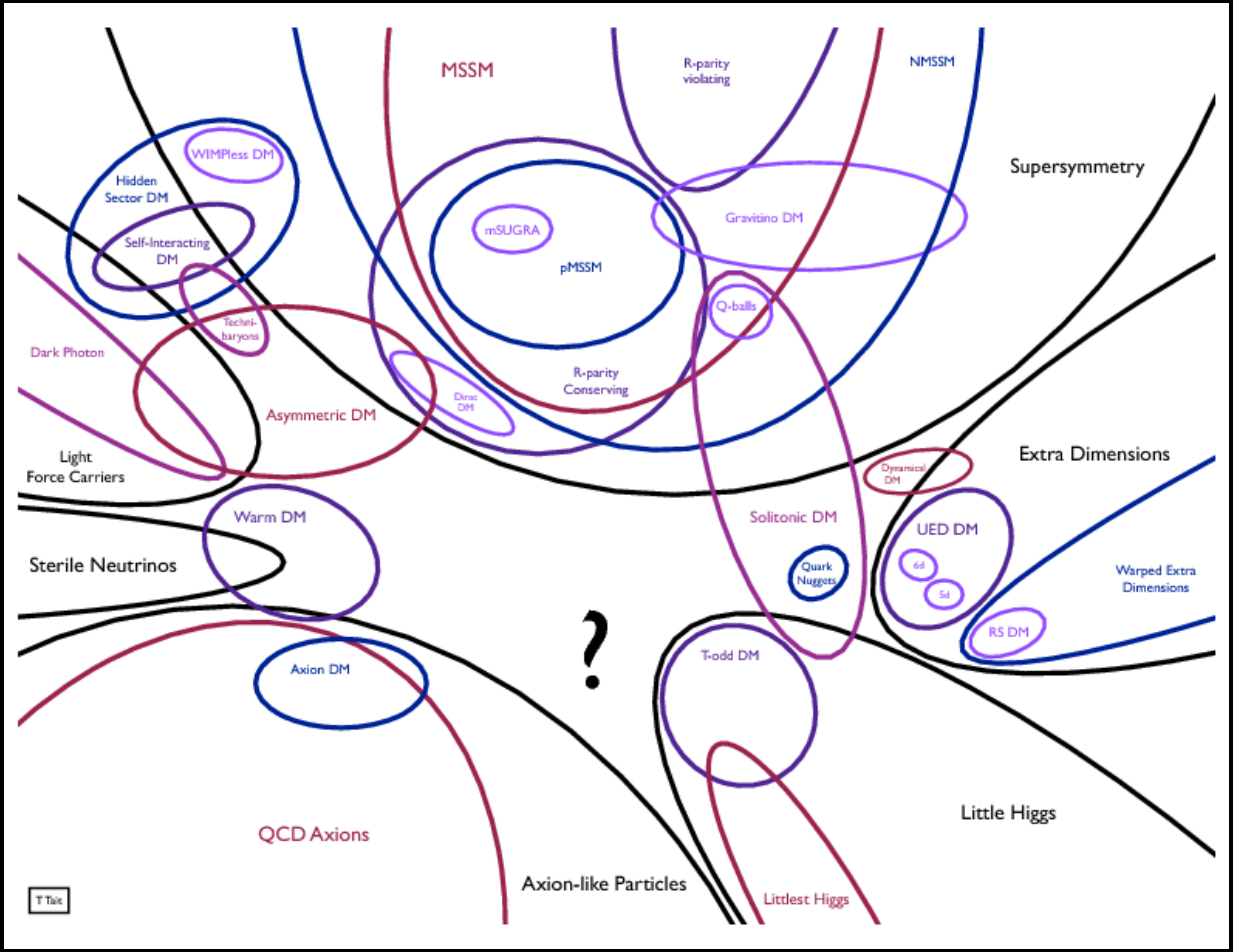
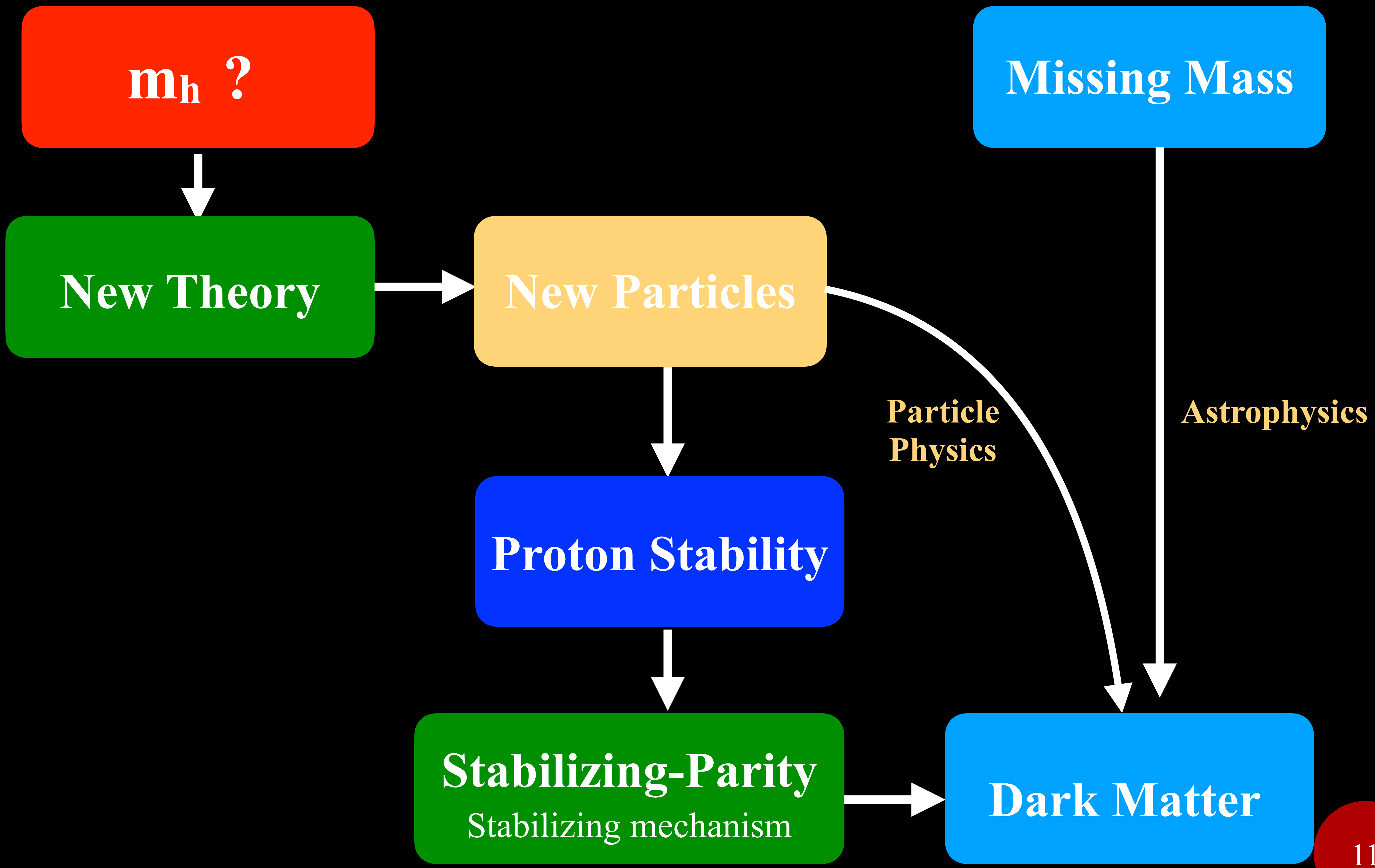


Image: ps.uci.edu

Range of possibilities is VAST

Solutions of hierarchy problem



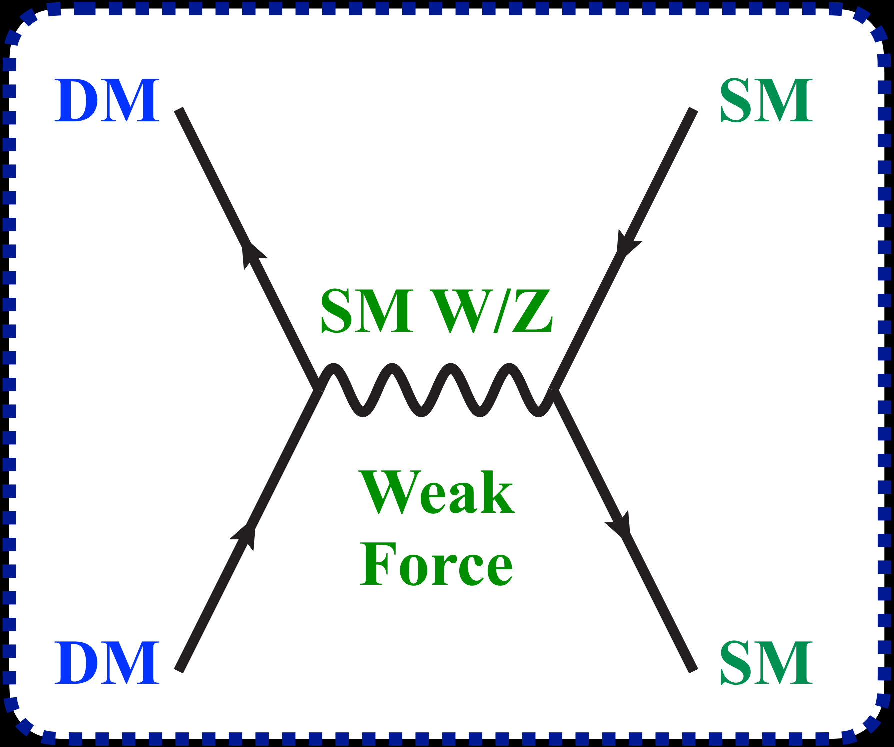
Solving the Hierarchy problem resulted in a perfect class of dark matter candidates called

Weakly-Interacting Massive Particles

"Electroweak" interactions ($W^{\pm}$, Z, h)

"weak-scale" mass
1 - 10 000 GeV

Explains: **Why so much dark matter around**



Dark matter annihilation

Observed **amount of dark matter** today → 'Relic Density'

$$\Omega h^2 \sim \frac{0.1\ \mathrm{pb}}{\langle \sigma v \rangle}$$

Weak scale
annihilation rate

In this lecture we will cover

1. How is dark matter produced in the early universe?

   How do we get its relic abundance?

2. How do we search for it today?

   In the sky (Indirect detection)

   In accelerator experiments

   Underground (Direct detection)

Relic density of dark matter

Expansion rate of the universe described by Hubble rate H(z)

In the standard model of cosmology called Lambda Cold Dark Matter (ΛCDM), Hubble rate is

$$H(z) = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_{rad}(1+z)^4 + \Omega_\Lambda}$$

Redshift- gives us an idea of cosmological time

Relic density of dark matter

Expansion rate of the universe described by Hubble rate H(z)

In the standard model of cosmology called Lambda Cold Dark Matter (ΛCDM), Hubble rate is

$$H(z) = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_{rad}(1+z)^4 + \Omega_\Lambda}$$

Hubble constant - standard constant to quantify universe expansion

Relic density of dark matter

Expansion rate of the universe described by Hubble rate H(z)

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$$H(z) = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_{rad}(1+z)^4 + \Omega_\Lambda}$$

Total matter in the universe -
includes SM and dark matter

$$\Omega_m = \Omega_c + \Omega_b$$

Relic density of dark matter

Expansion rate of the universe described by Hubble rate H(z)

In the standard model of cosmology called Lambda Cold Dark Matter (ΛCDM), Hubble rate is

$$H(z) = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_{rad}(1+z)^4 + \Omega_\Lambda}$$

Total amount of radiation in the universe - relativistic free particles like photons, neutrinos

Relic density of dark matter

Expansion rate of the universe described by Hubble rate H(z)

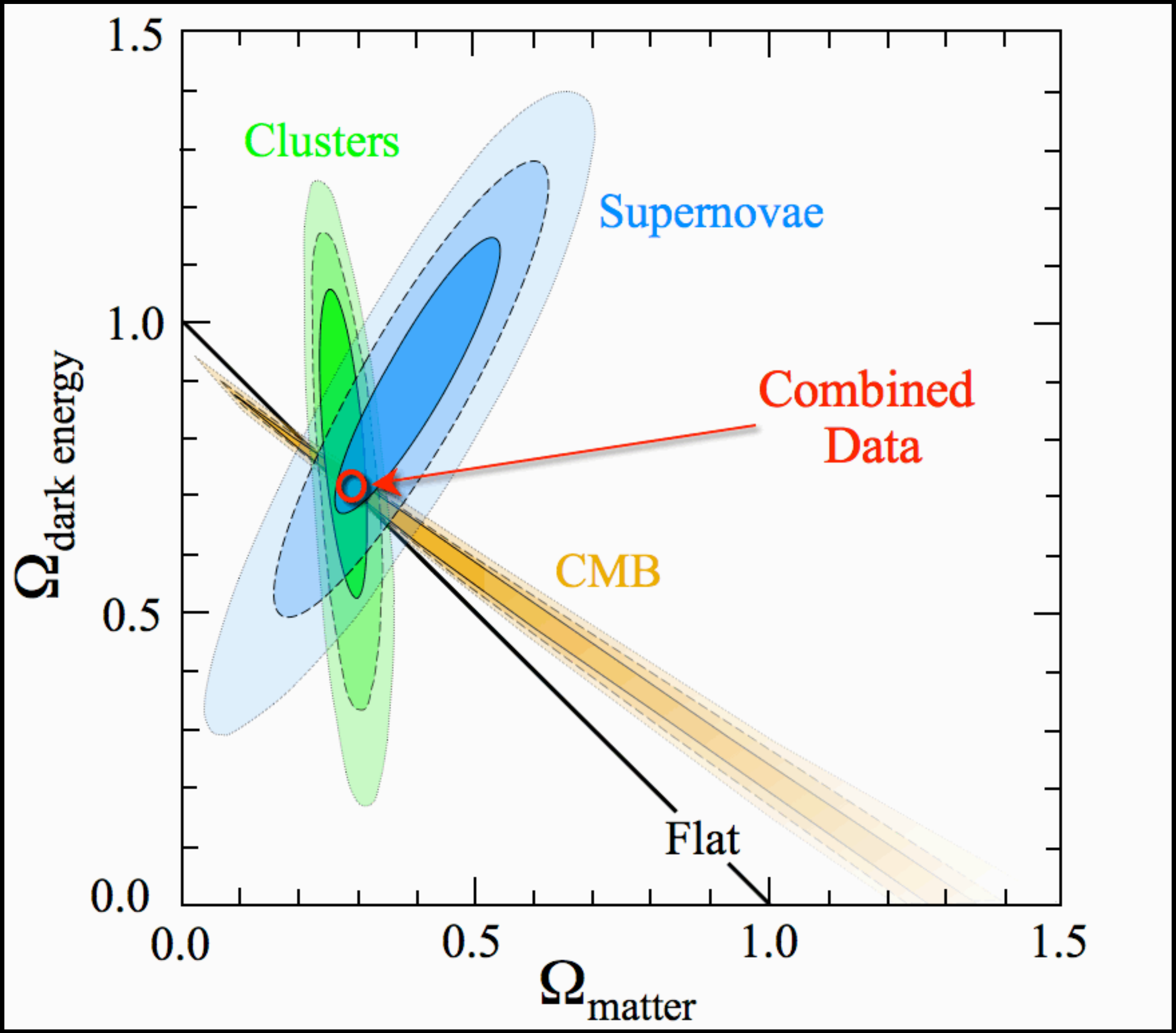
In the standard model of cosmology called Lambda Cold Dark Matter (ΛCDM), Hubble rate is

$$H(z) = H_0 \sqrt{\Omega_m (1+z)^3 + \Omega_{rad} (1+z)^4 + \Omega_\Lambda}$$

Dark energy density - phenomenon making universe expand

Relic density of dark matter

Using combined data from a variety of telescopes measuring billions of galaxies, CMB and supernovae, we can fit those parameters.



(See lectures by Prof. de Naurois)

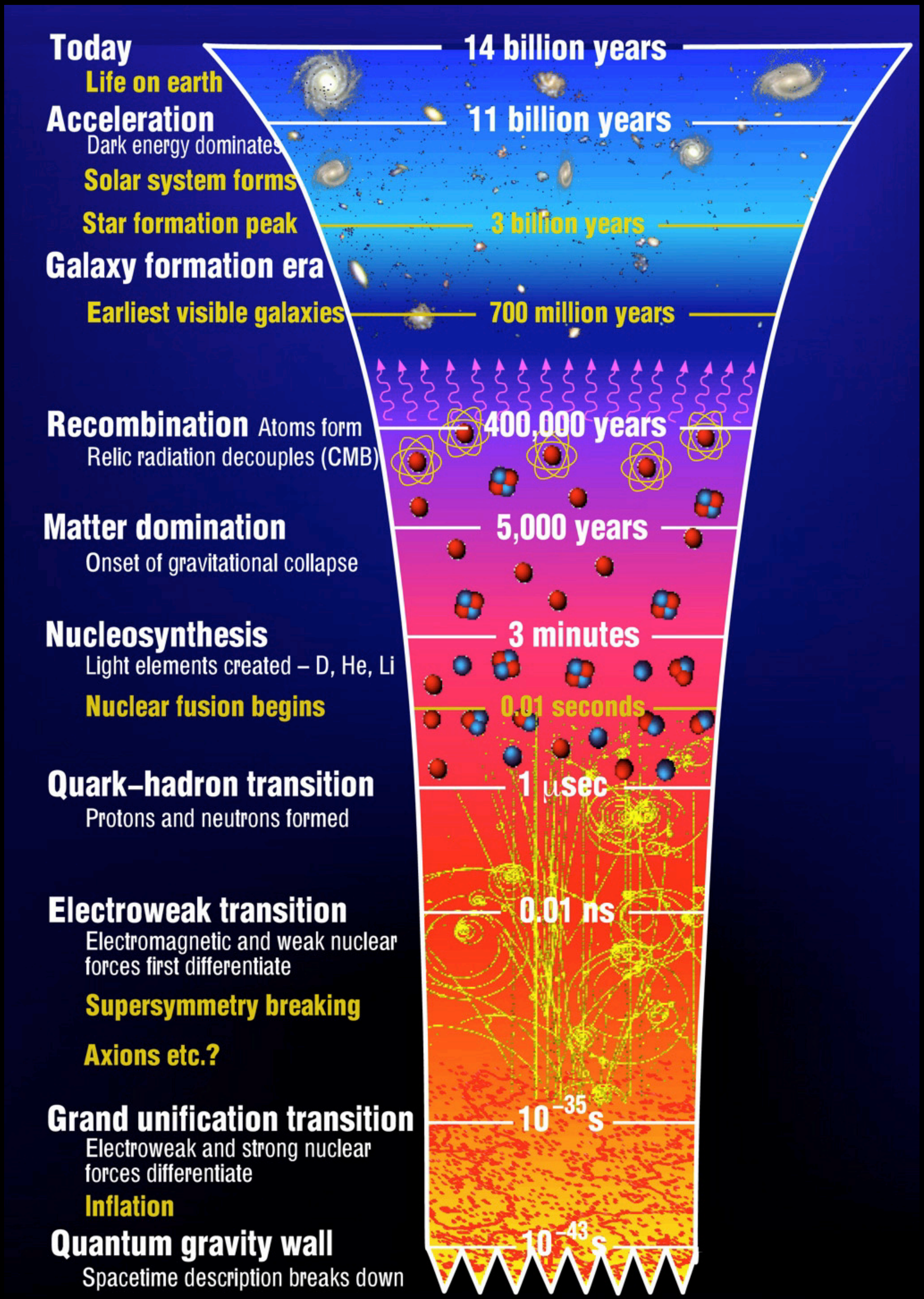
Relic density of dark matter

Using combined data from a variety of telescopes measuring billions of galaxies, CMB and supernovae, we can fit those parameters.

Parameter	TT+lowP+lensing 68% limits	TT,TE,EE+lowP+lensing+ext 68% limits
n_s	0.9677 ± 0.0060	0.9667 ± 0.0040
H_0	67.81 ± 0.92	67.74 ± 0.46
Ω_Λ	0.692 ± 0.012	0.6911 ± 0.0062
Ω_m	0.308 ± 0.012	0.3089 ± 0.0062
$\Omega_b h^2$	0.02226 ± 0.00023	0.02230 ± 0.00014
$\Omega_c h^2$	0.1186 ± 0.0020	0.1188 ± 0.0010
σ_8	0.8149 ± 0.0093	0.8159 ± 0.0086
z_{re}	$8.8^{+1.7}_{-1.4}$	$8.8^{+1.2}_{-1.1}$
Age/Gyr	13.799 ± 0.038	13.799 ± 0.021

Dark matter relic density from cosmological data

What is Relic density?



- Amount of dark matter left over today from the hot dense plasma after Universe expands and cools

- Amount of DM referred to as **relic -** i.e. relic of the early universe

- **Relic density** can also tell us how **DM** was produced in early universe

Why is Relic Density Important?

Any method of DM production in early Universe must match cosmological measurements of relic density

Any theory predicting that dark matter is produced via a certain method, must match relic density from cosmological observations

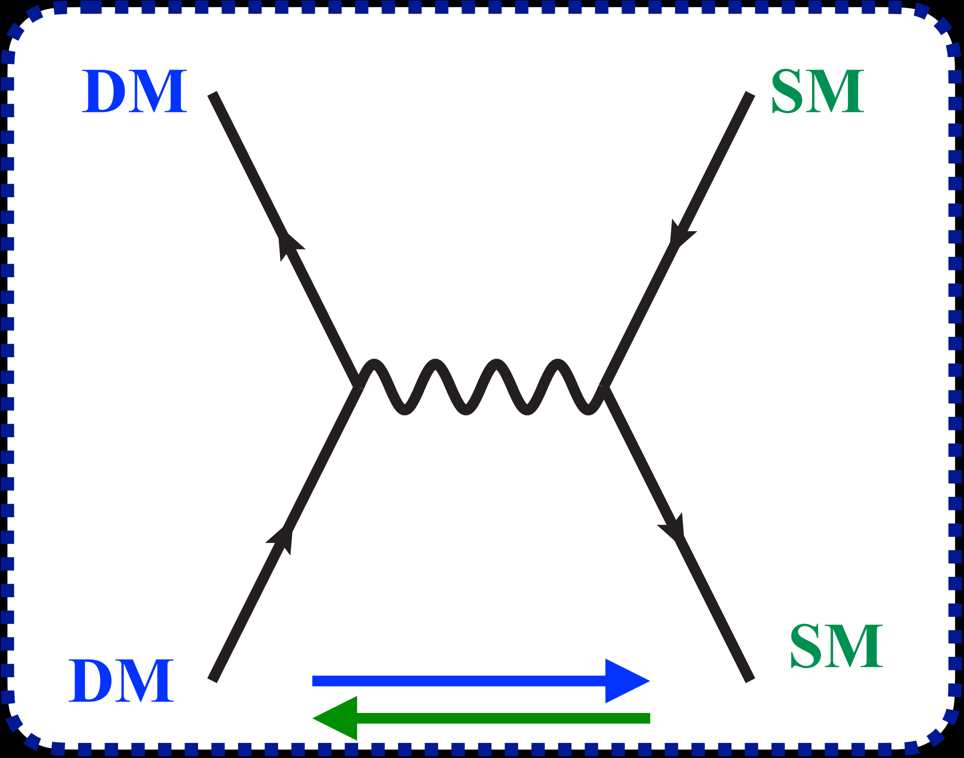
$$\Omega_c h^2 \sim 0.12$$

This is important because it allows the identification of theory parameter space that is interesting and predictive, giving us a clue where to start searching for dark matter

Dark matter production in the early universe

e.g. Thermal Freeze-out

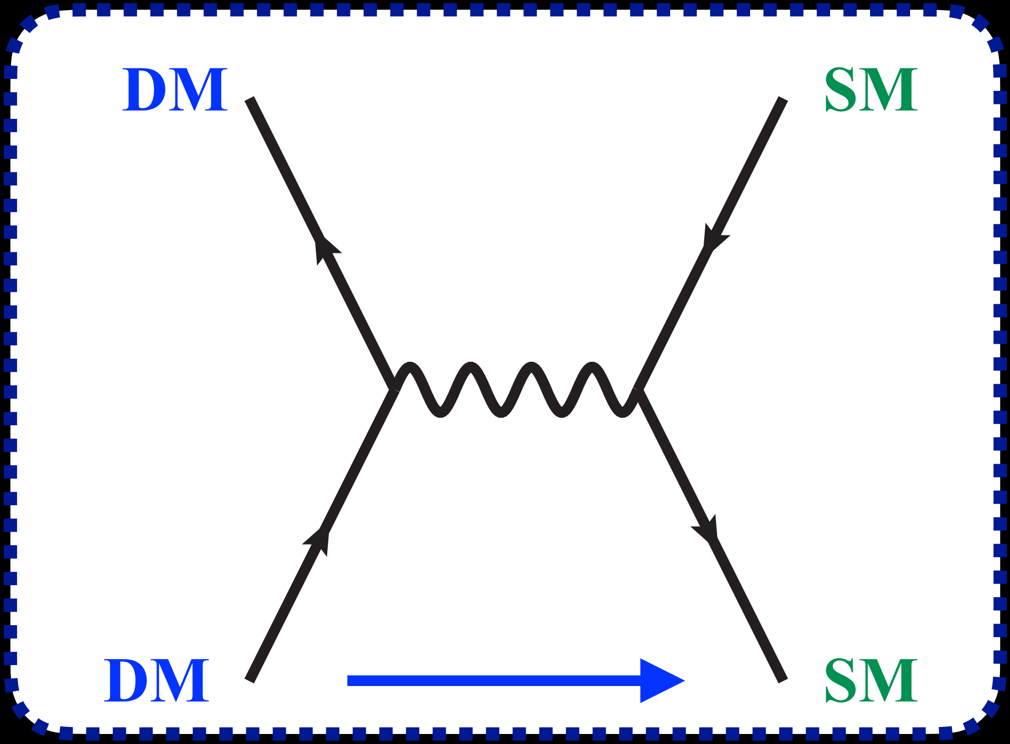
- After big bang, universe is in hot dense plasma of dark sector & SM particles. Plasma is hot enough that



DM and SM are in **thermal equilibrium**

i.e. both particles can be explained by one common temperature

- As universe expands and cools SM cannot convert to DM anymore, only forward process occurs



- As universe keeps expanding, two DM particles cannot find each other to annihilate into SM particles

- **Dark matter has now frozen out and relic number density is set**

Evolution of dark matter number density as Universe expands is given by Boltzmann equation

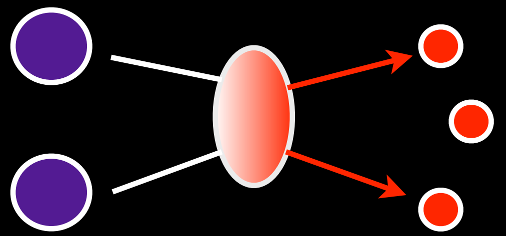
Dark matter number density

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle\left[n_\chi^2 - (n_\chi^{eq})^2\right]$$

Hubble Friction

Annihilation

$H \sim g_* \frac{T^2}{M_{\rm Pl}}$



Describes DM number as universe expands

Evolution of dark matter number density as Universe expands is given by **Boltzmann equation**

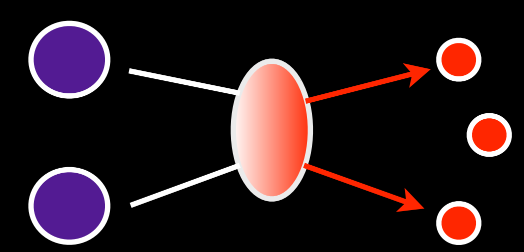
Particles physics enters here

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma v \rangle \left[n_\chi^2 - (n_\chi^{eq})^2 \right]$$

Hubble Friction

$$H \sim g_* \frac{T^2}{M_{\rm Pl}}$$

Annihilation



Thermally averaged annihilation cross-section: probability that two DM particles traveling in some velocity distribution will find each other and annihilate into SM particles.

Evolution of dark matter number density as Universe expands is given by Boltzmann equation

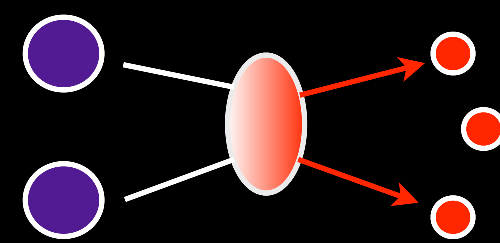
Particles physics enters here

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma v \rangle \left[n_\chi^2 - (n_\chi^{eq})^2 \right]$$

Hubble Friction

$$H \sim g_* \frac{T^2}{M_{\rm Pl}}$$

Annihilation



DM number density at equilibrium, given by

$$n_\chi^{eq} = g \left(\frac{mT}{2\pi} \right)^{3/2} e^{-m/T}$$

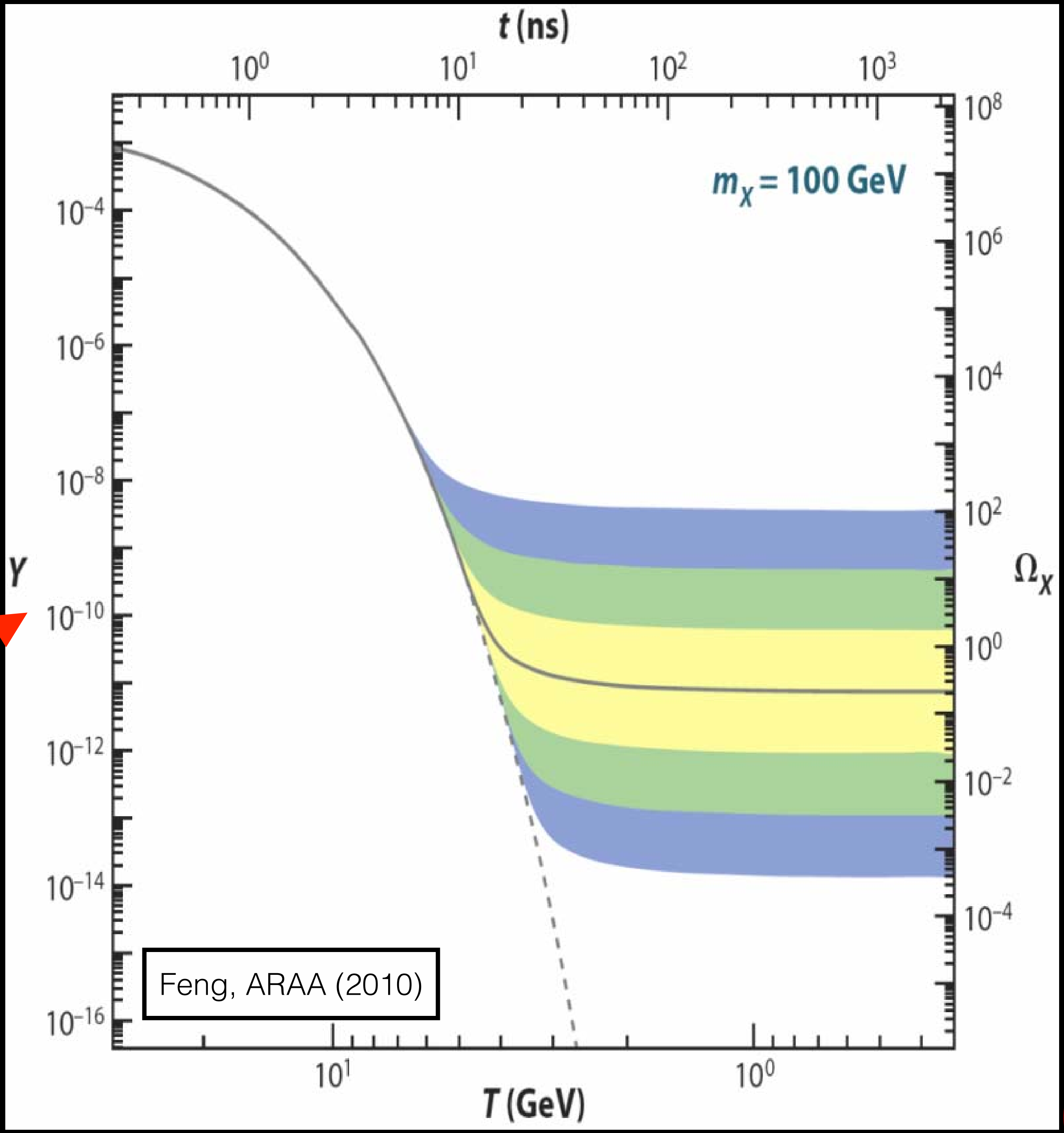
Rewrite **Boltzmann equation** as

$$\frac{dY}{dx} = -\frac{x\,\langle\sigma v\rangle\, s}{H(m)}\left(Y^2 - Y_{eq}^2\right)$$

Comoving number density is $Y = \frac{n_\chi}{s}$

temperature of the universe $x = \frac{m}{T}$

Solution of Boltzmann equation

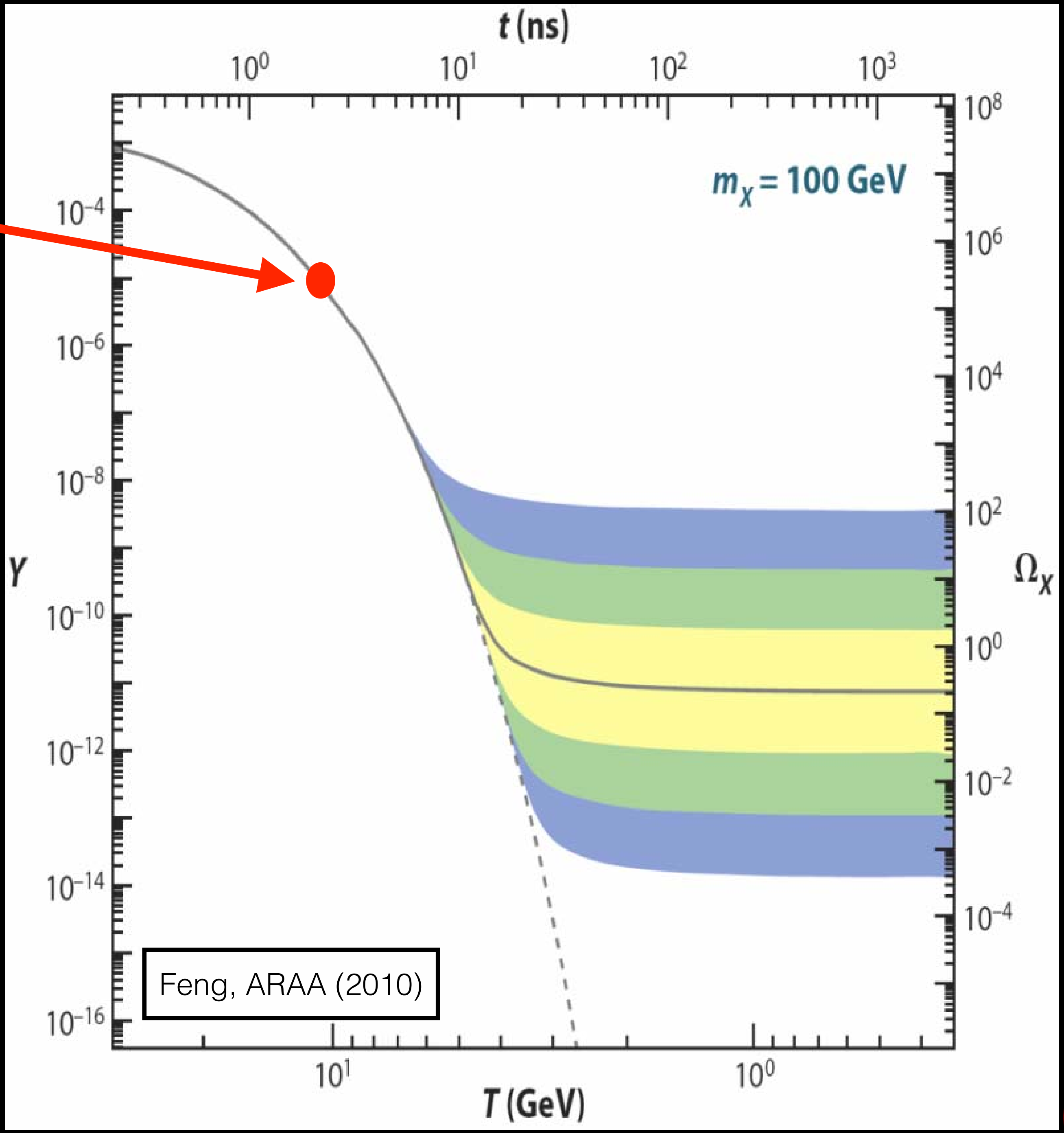


Rewrite **Boltzmann equation** as

$$\frac{dY}{dx} = -\frac{x \langle \sigma v \rangle s}{H(m)} (Y^2 - Y_{eq}^2)$$

DM number density at equilibrium

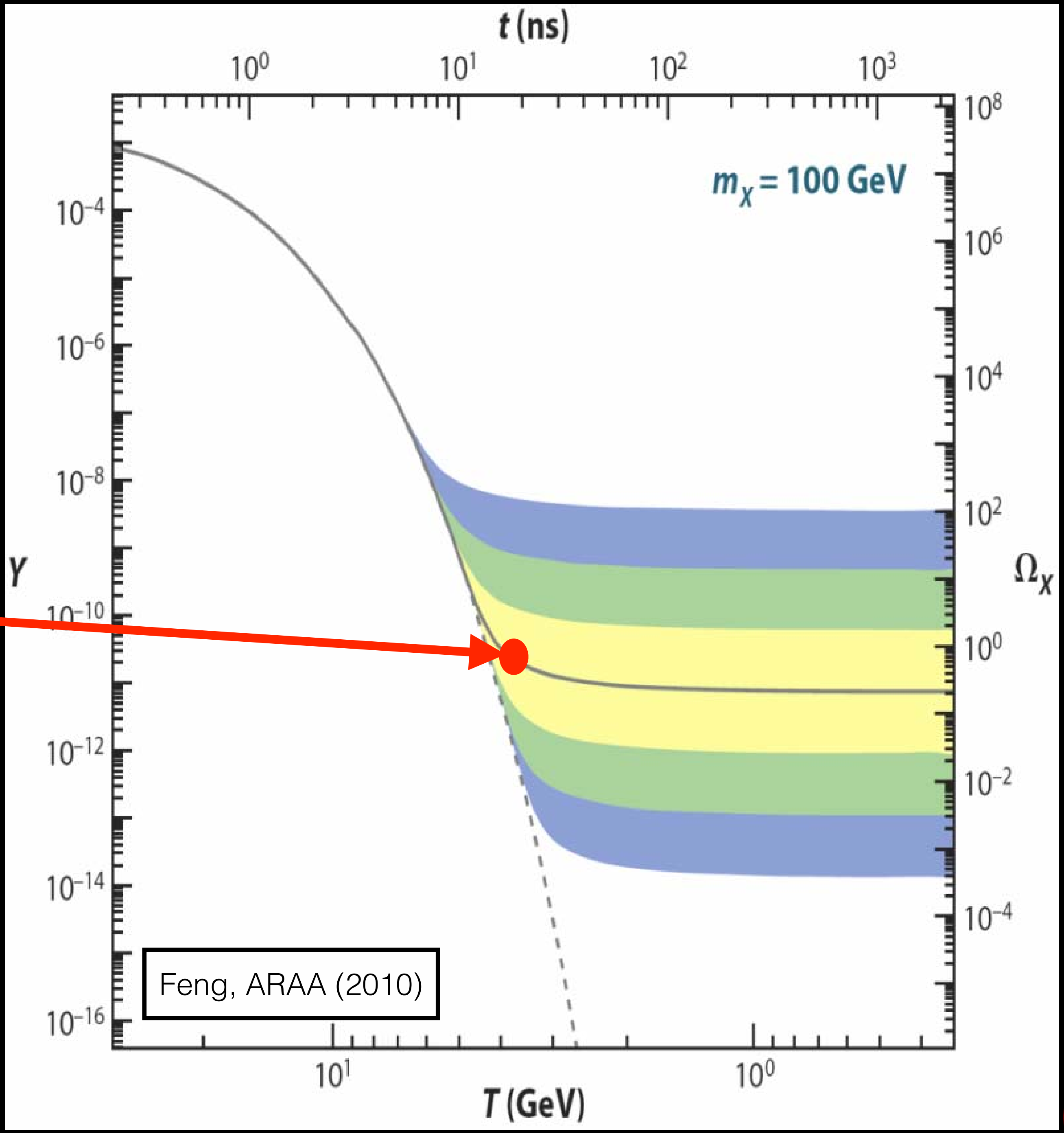
Keeps exponentially decreasing as universe expands and cools and DM converts to SM particles



Rewrite **Boltzmann equation** as

$$\frac{dY}{dx} = -\frac{x \langle \sigma v \rangle s}{H(m)} (Y^2 - Y_{eq}^2)$$

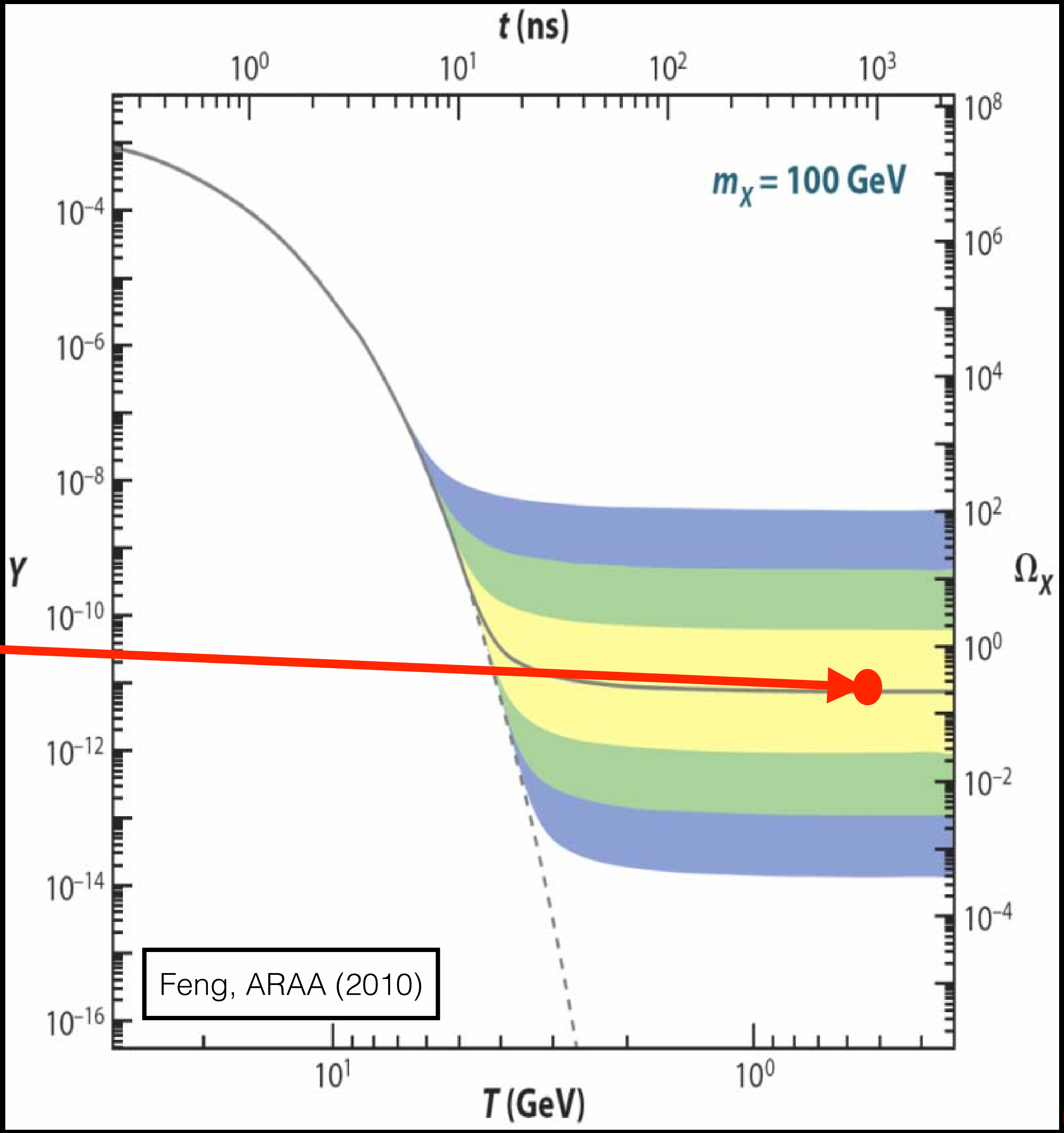
DM Freezes out, particles are no longer able to find each other to annihilate away into SM



Rewrite Boltzmann equation as

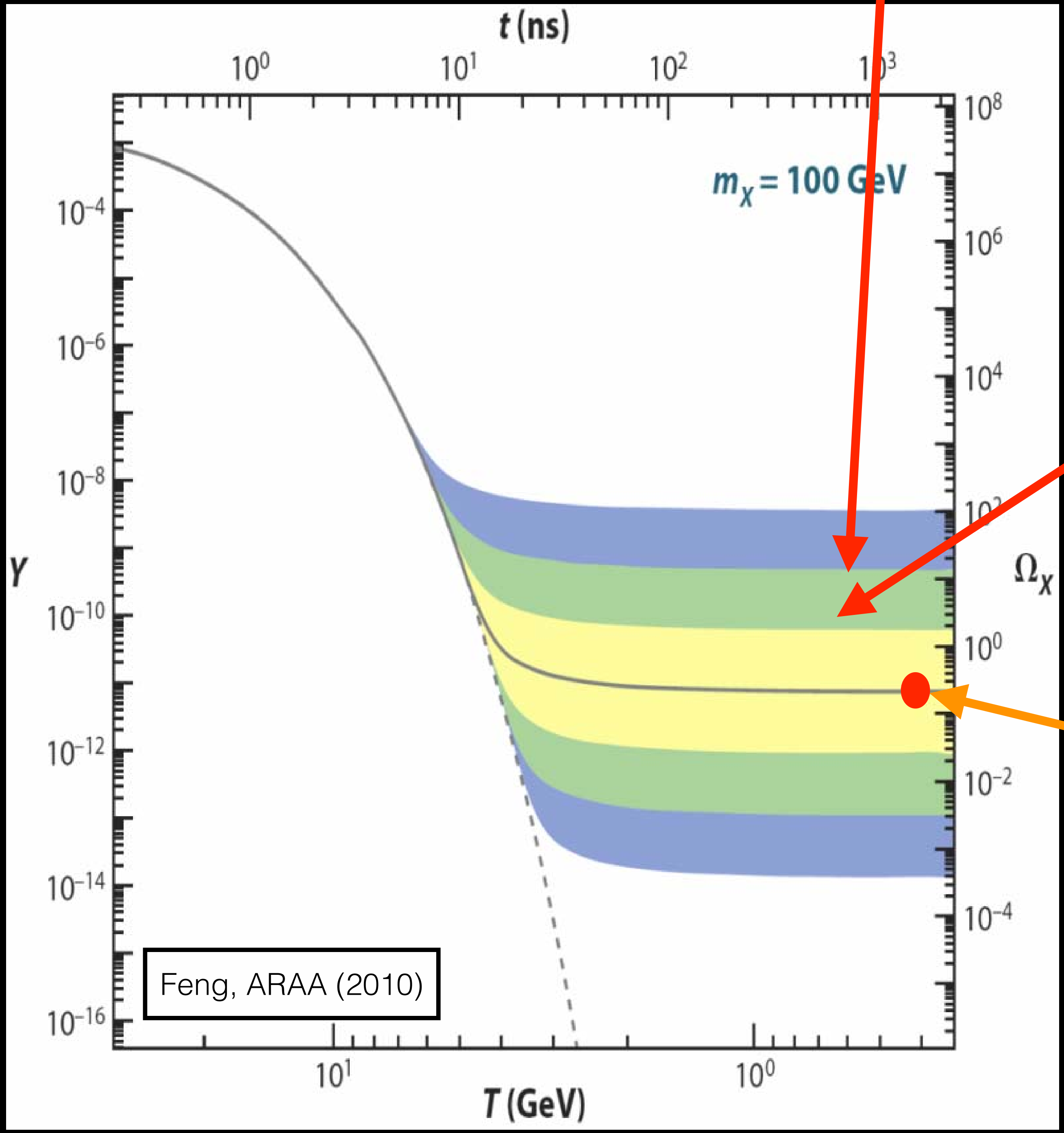
$$\frac{dY}{dx} = -\frac{x\,\langle \sigma v \rangle\, s}{H(m)}\left(Y^2 - Y_{eq}^2\right)$$

DM number density we observe in the universe today



Rewrite Boltzmann equation as

$$\frac{dY}{dx} = -\frac{x\,\langle\sigma v\rangle\, s}{H(m)}(Y^2 - Y_{eq}^2)$$



Controlled by strength of particle physics interactions

$\Omega_c h^2 \sim 0.12$

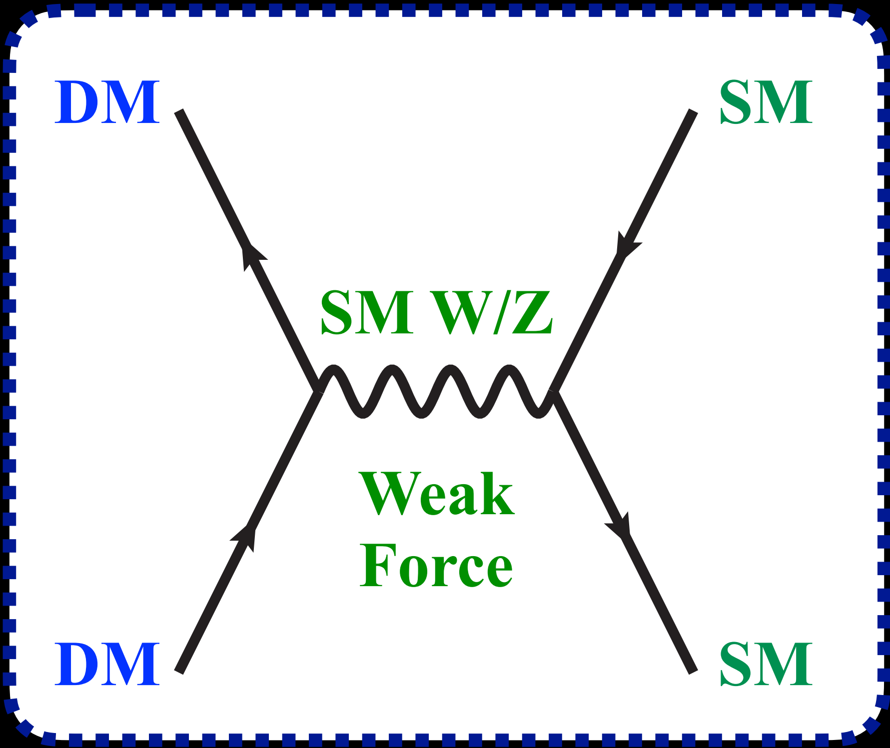
WIMP Miracle

Weakly-Interacting Massive Particles

“Electroweak” interactions ($W^{\pm}$, Z, h)

“weak-scale” mass
1 - 10 000 GeV

Calculations of relic density match cosmological observations almost exactly



Dark matter annihilation

$$\Omega h^2 \sim \frac{0.1\ \text{pb}}{\langle \sigma v \rangle} \sim 0.12$$

Weak scale
annihilation rate

How do we find dark matter?

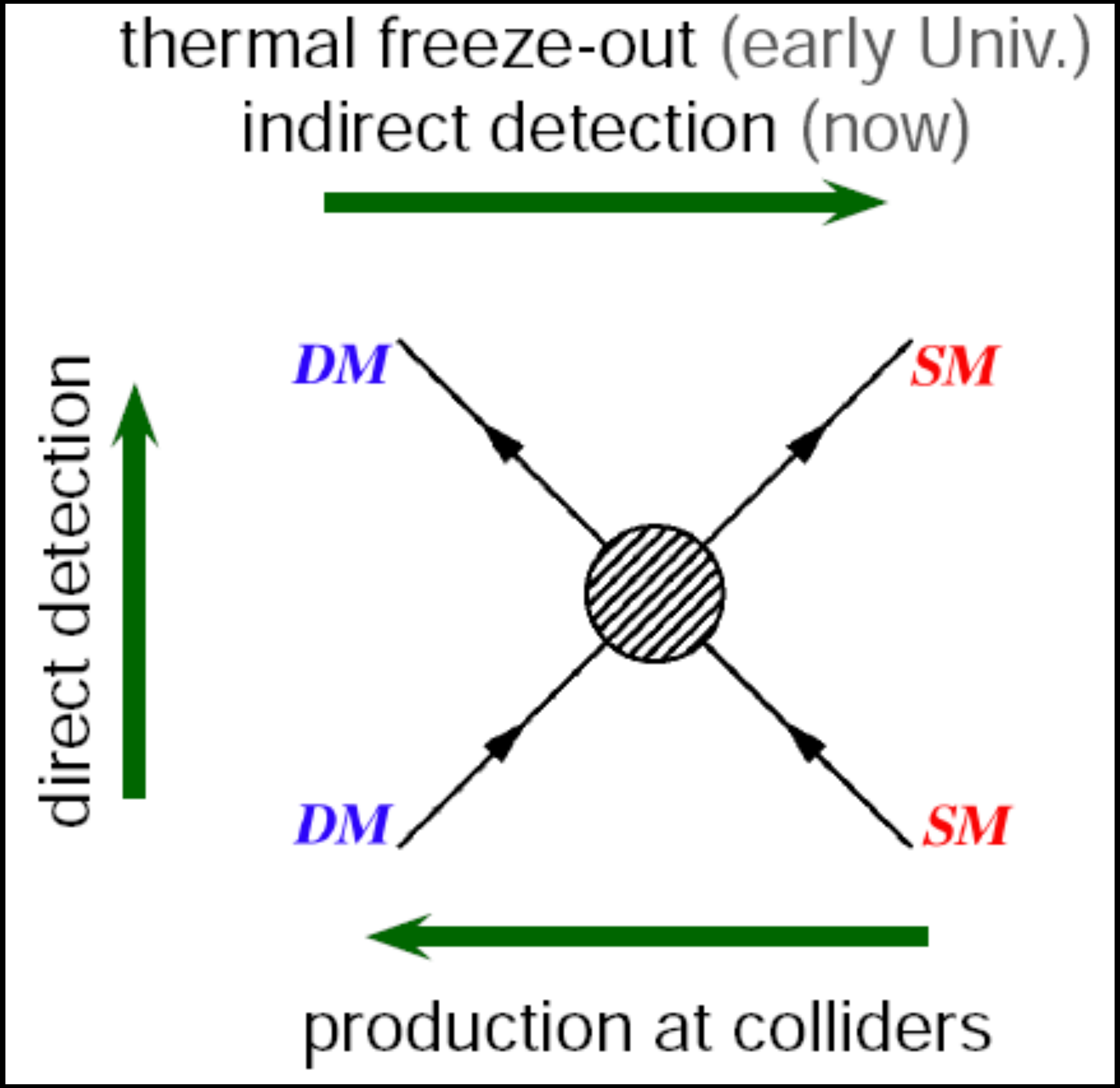


Image: cosmo17.in2p3.fr

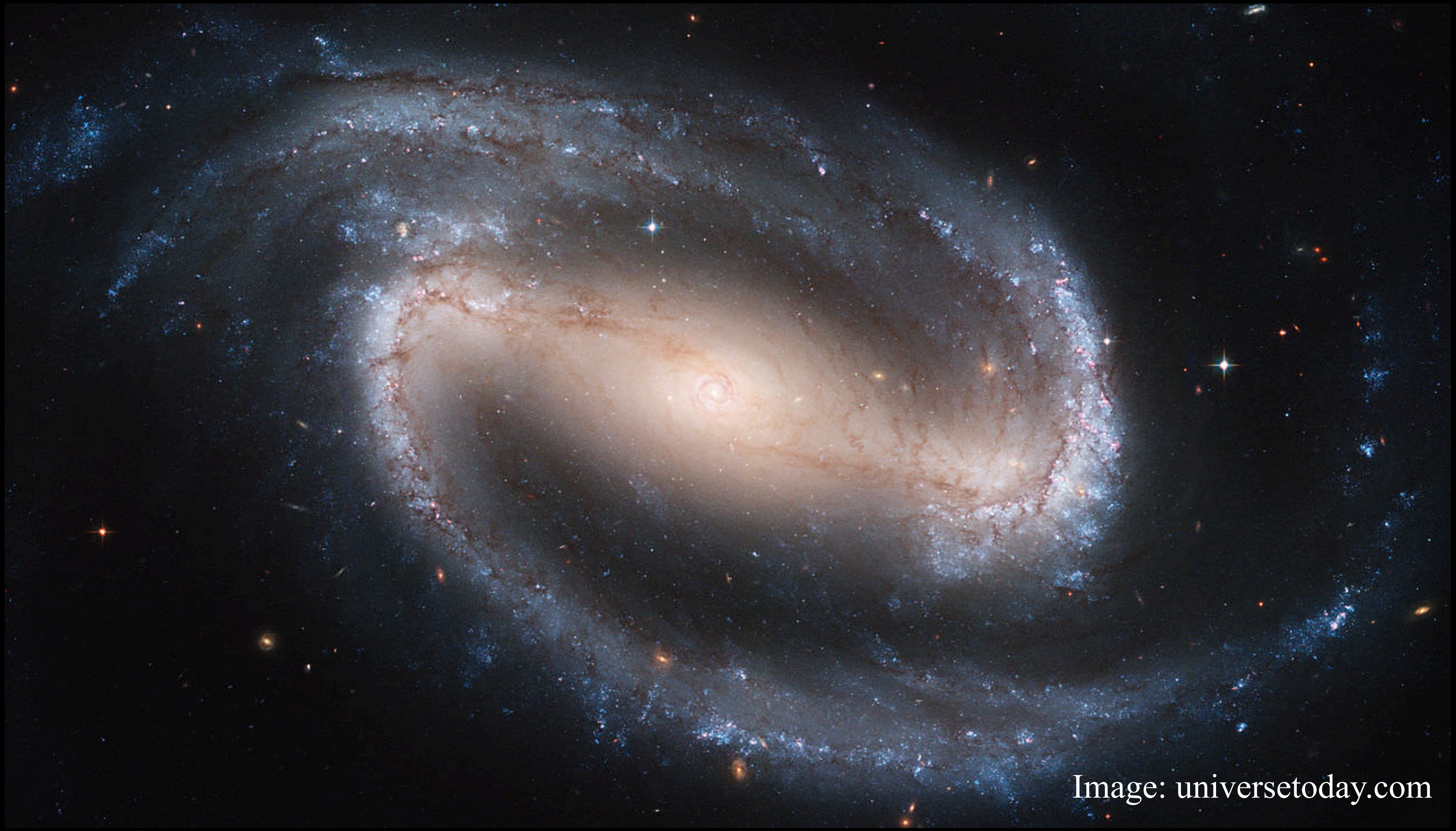
In the Sky

At Colliders

In underground detectors

Indirect detection

In Dark matter dense regions like the Galactic center:

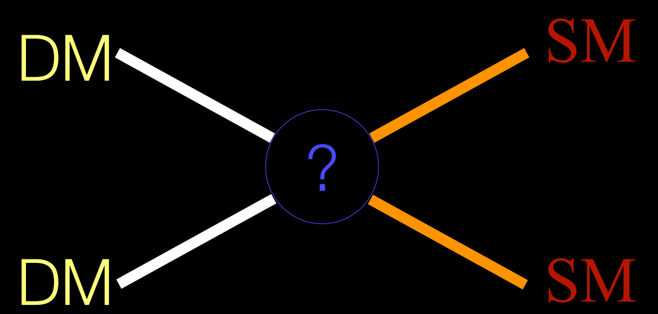


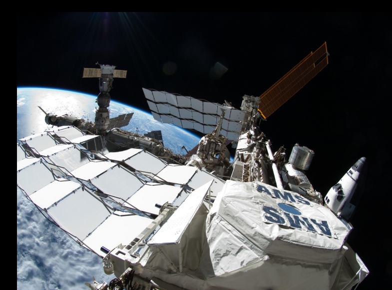
Dark matter particles find each other and annihilate into SM particles

Dark matter particles may decay into SM particles

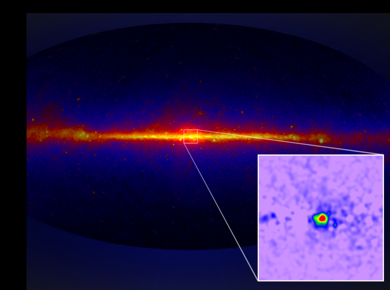
We must look where dark matter density is highest

annihilation

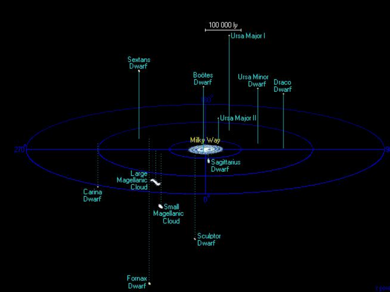




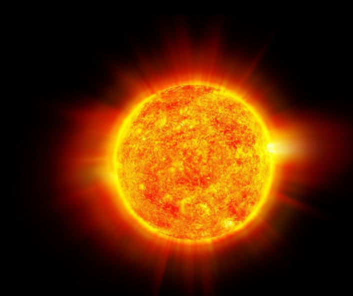
Local halo



Galactic centre, other galaxies

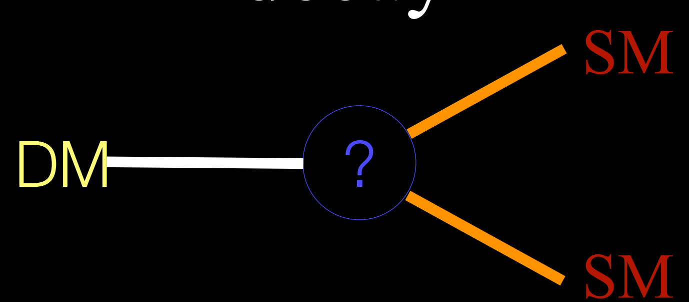


Dwarf galaxies

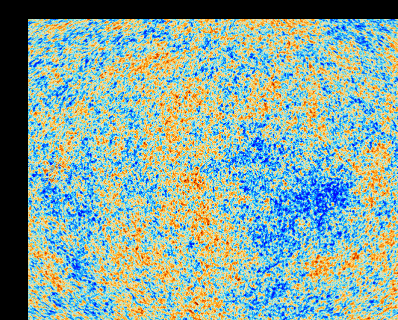


The Sun

decay



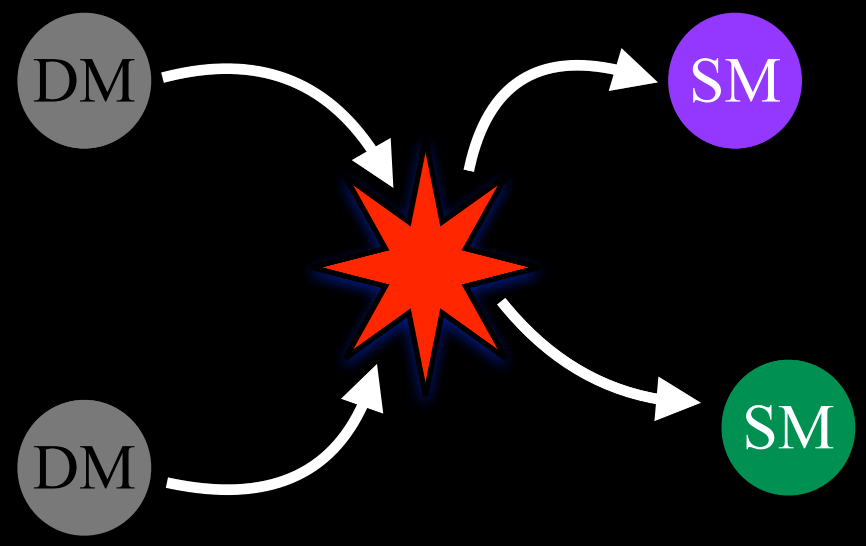
Galaxy Clusters

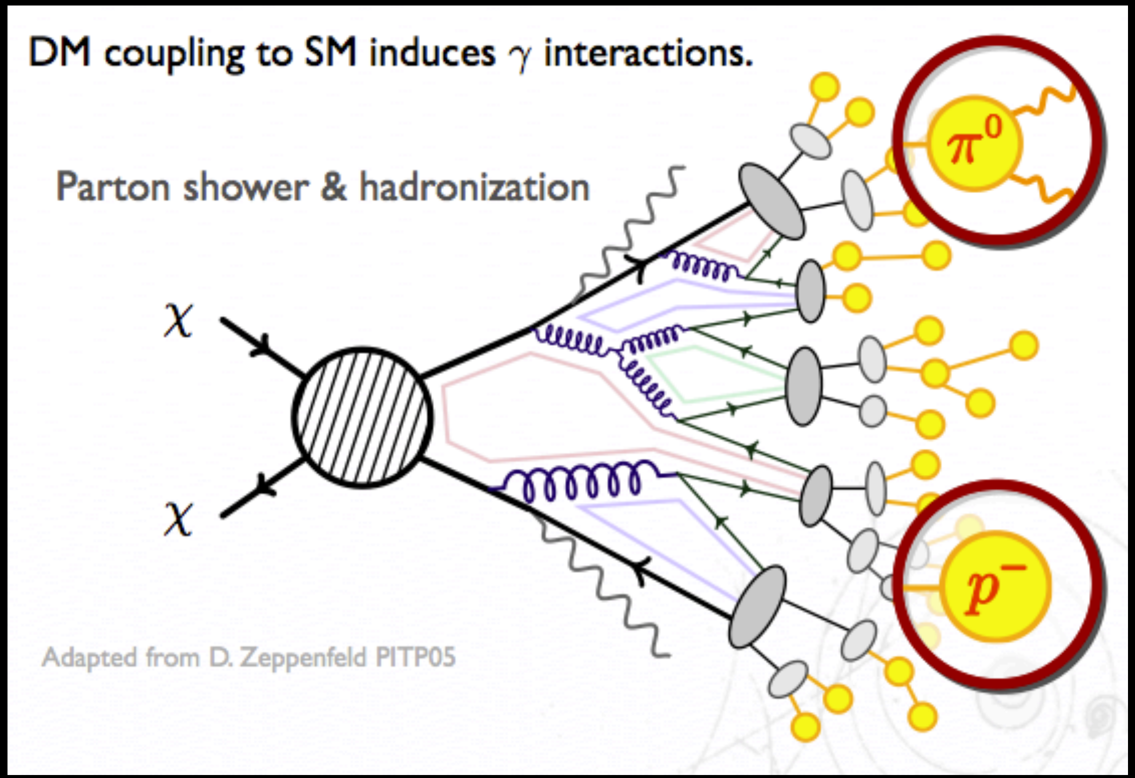


The entire Universe

Indirect Detection

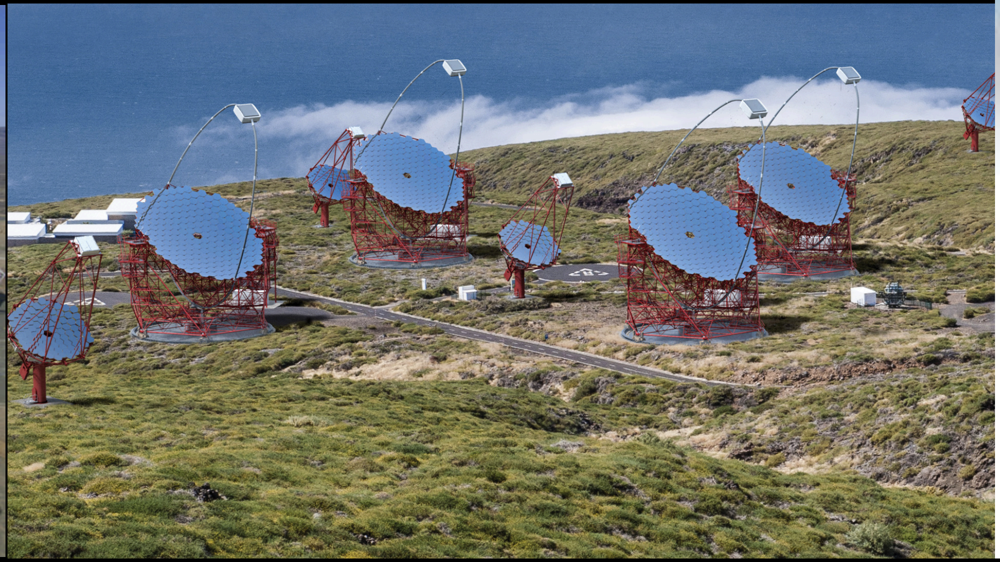
Dark Matter annihilates / decays into SM particles



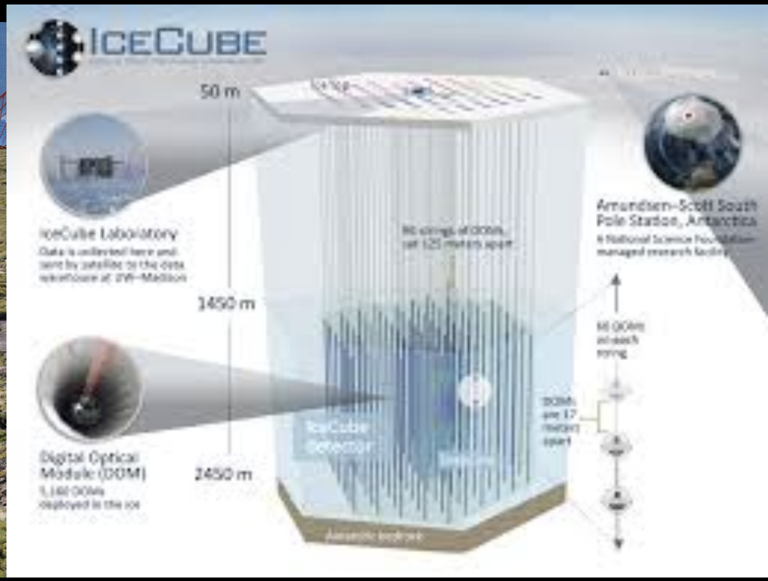


Square Kilometer Array

H.E.S.S / Cherenkov Telescope Array

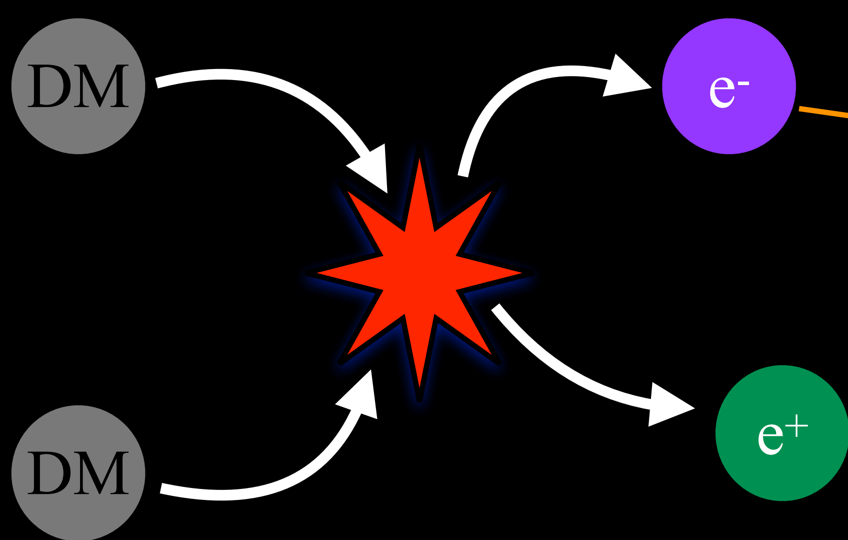


IceCUBE neutrino observatory

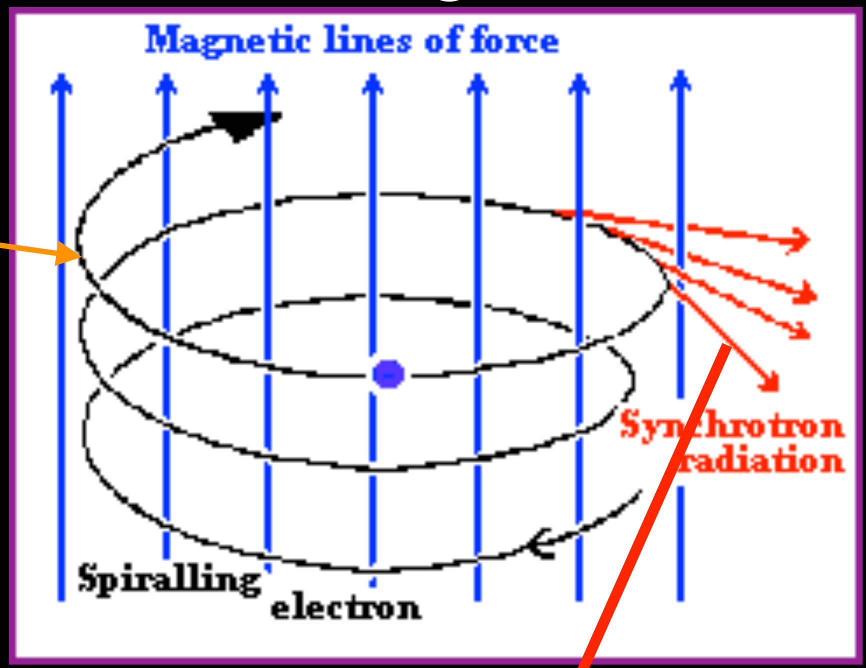


e.g Synchrotron Radiation

Dark Matter annihilates to charged SM particles like electrons/positrons



Galactic magnetic fields



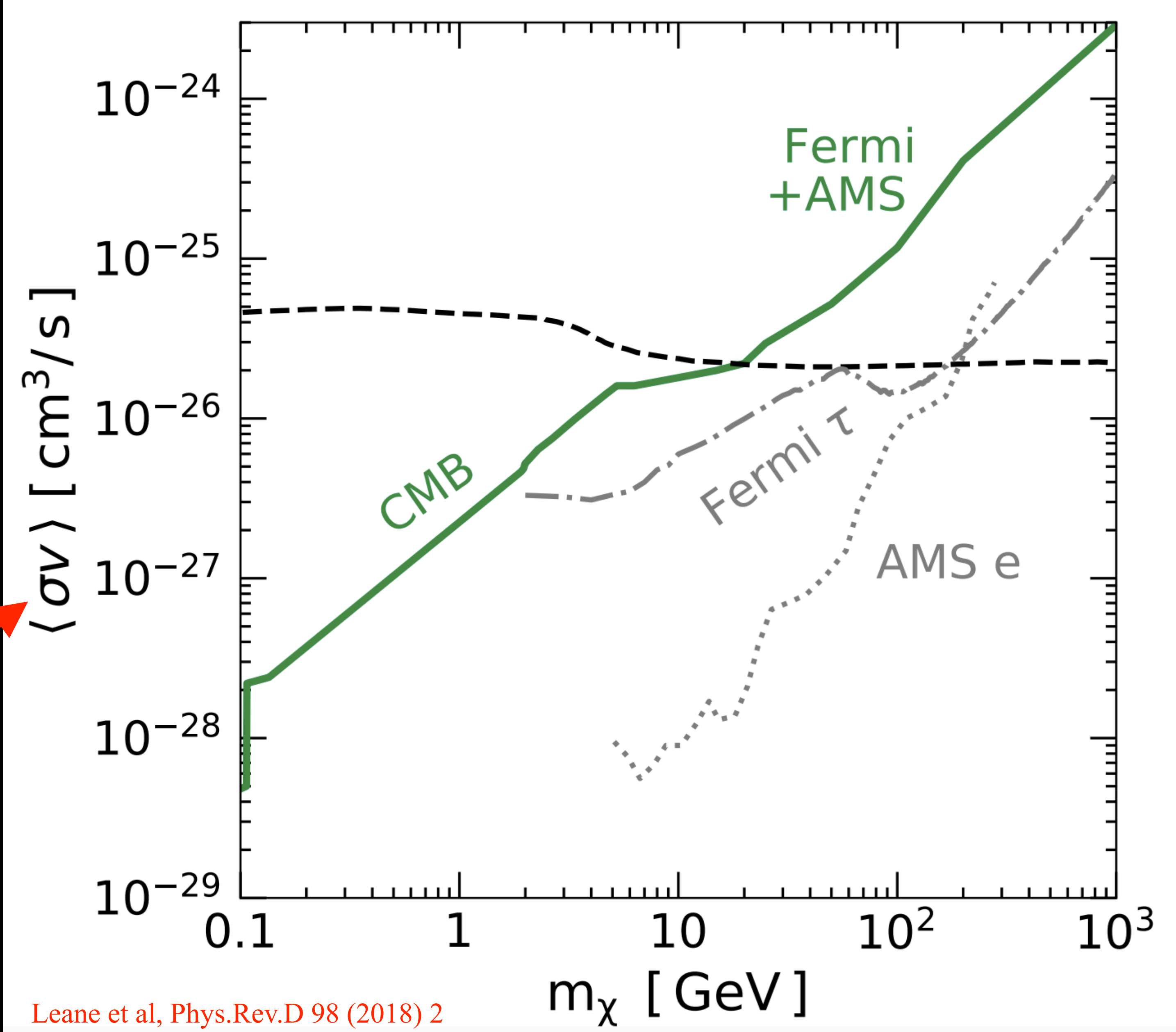
Square Kilometer Array

Indirect Detection

$$\frac{d\phi}{dE_\gamma} \sim \left(\frac{\langle\sigma v\rangle}{8\pi}\frac{dN_\gamma}{dE_\gamma}\frac{1}{m_\chi^2}\right)\int_{\Delta\Omega}\int_{l.o.s}\rho_\chi^2(l)\,dl\,d\Omega$$

Flux of photons from DM annihilation

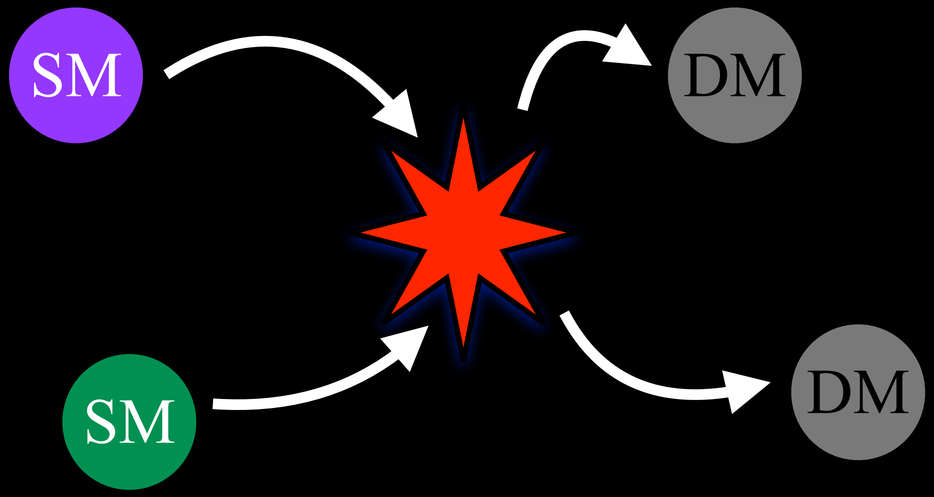
Compared with data from telescopes to obtain limits on DM parameters

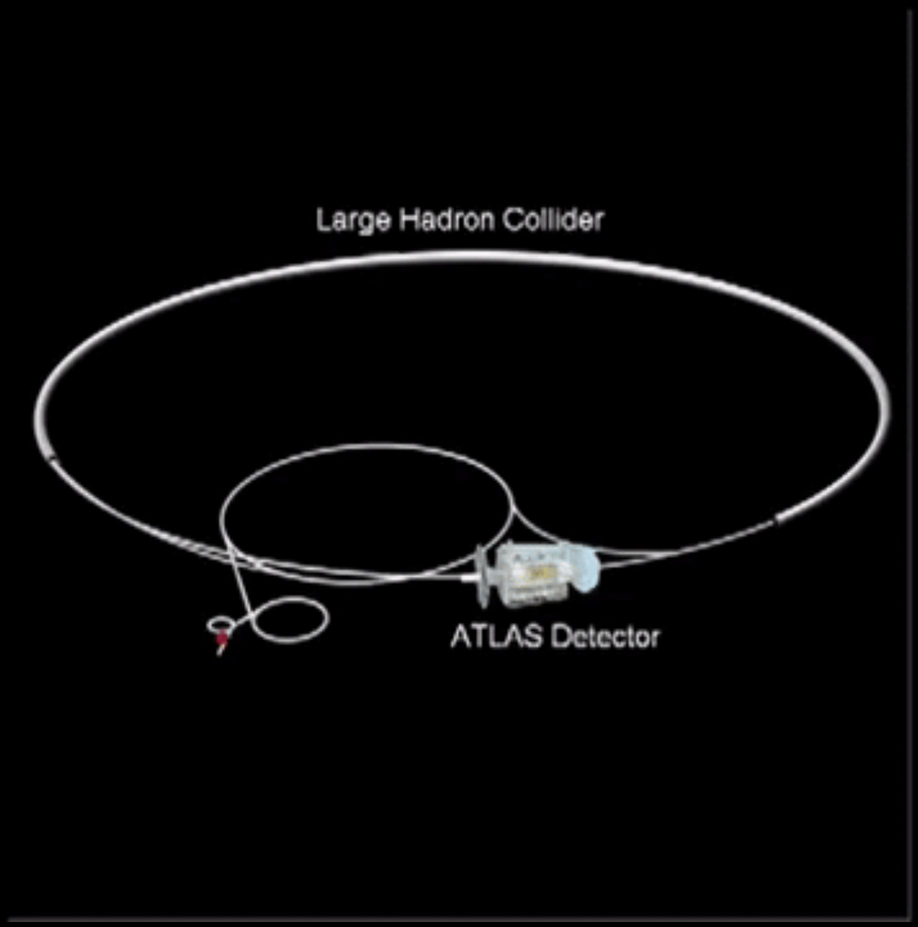


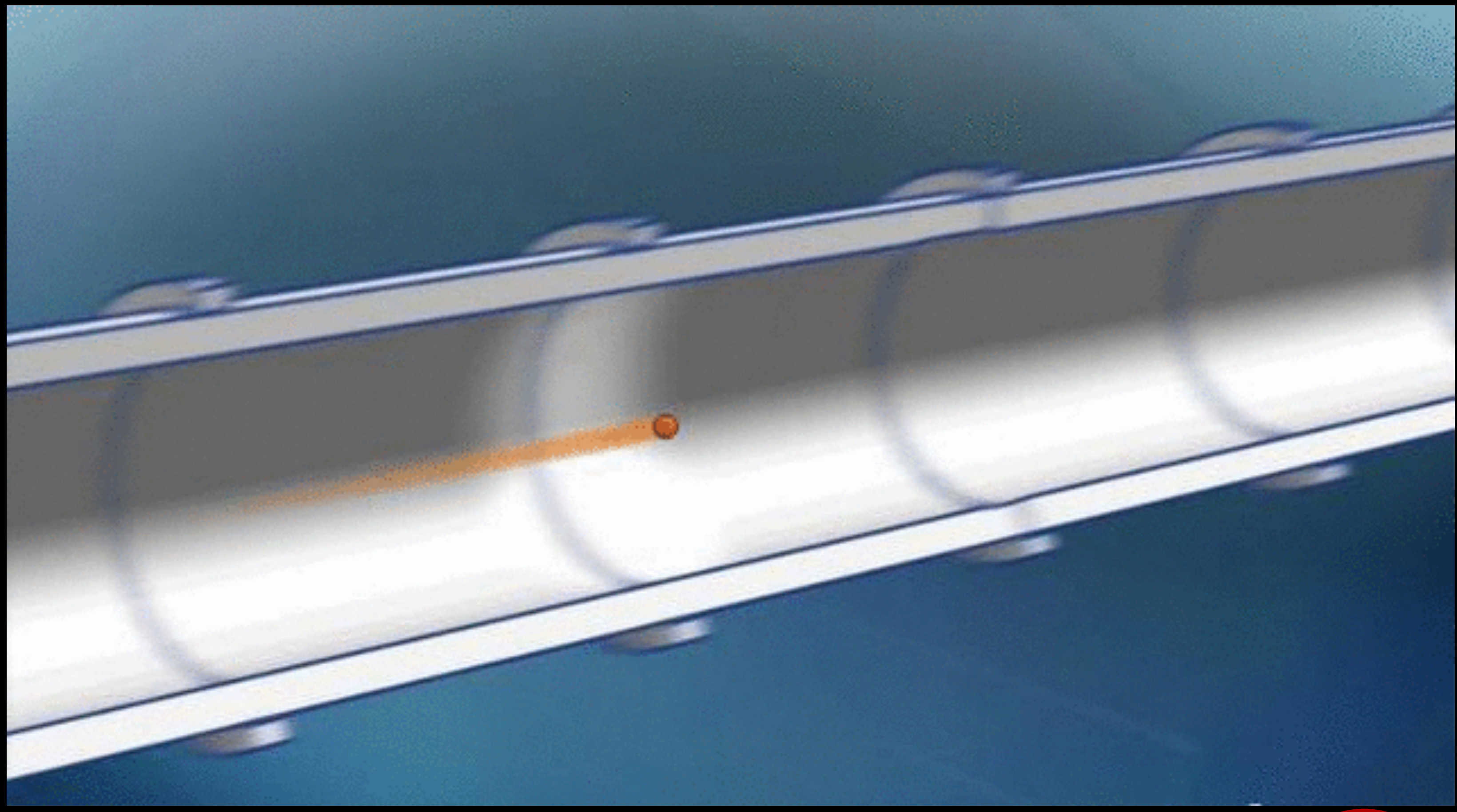
Leane et al, Phys.Rev.D 98 (2018) 2

Production at Colliders/Accelerators

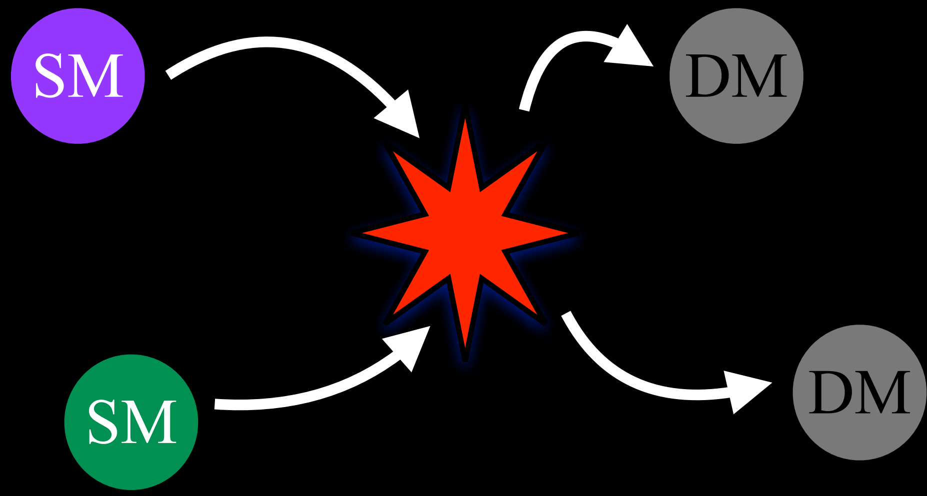
Collide SM particles to produce dark matter in the Laboratory







Production at Colliders/Accelerators



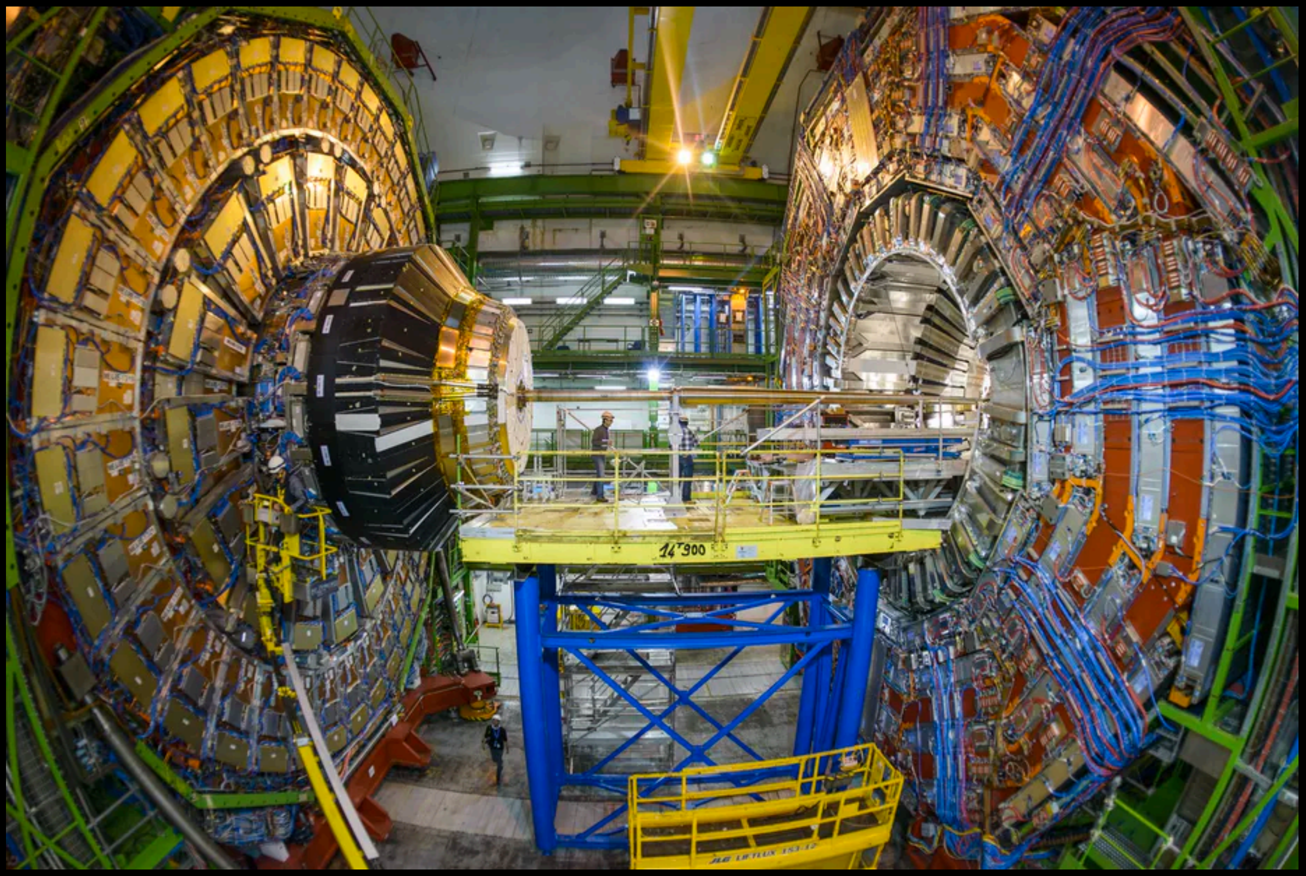


Image: theconversation.com

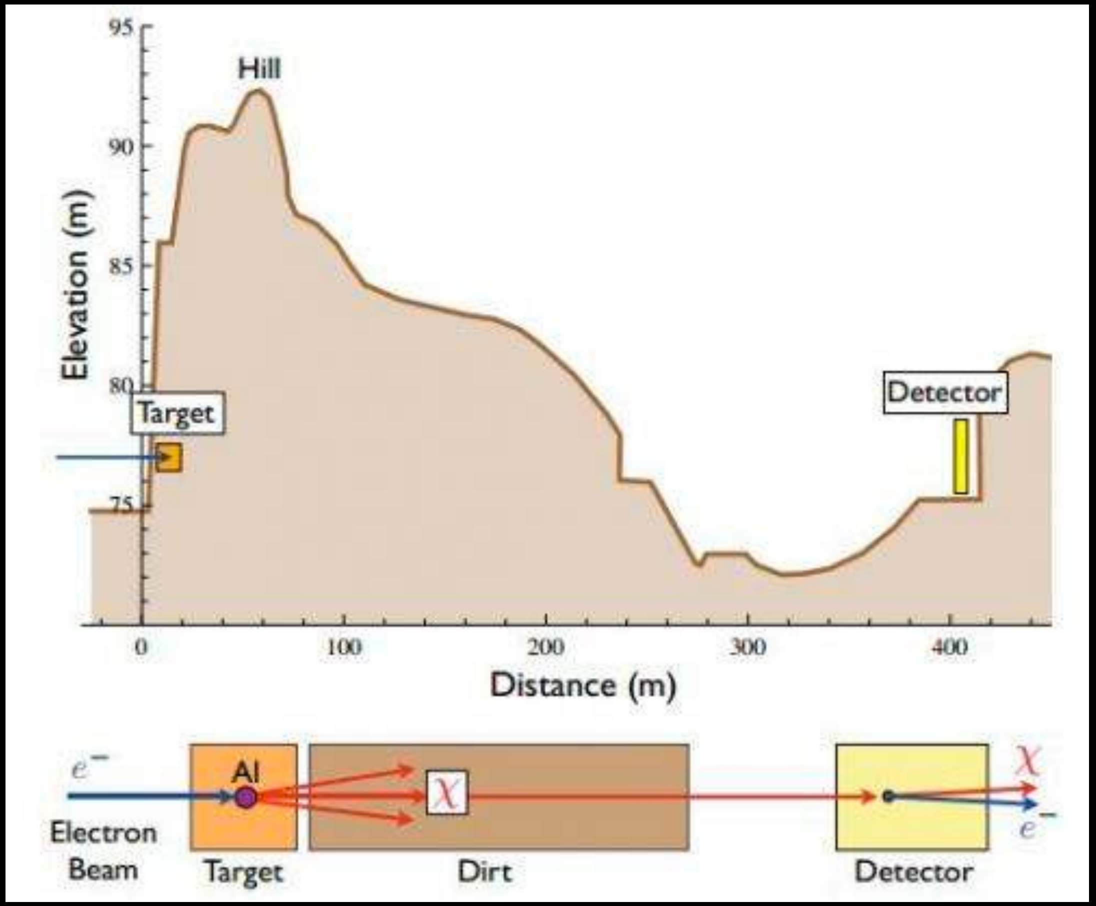


Image: phys.org

High/low energy colliders

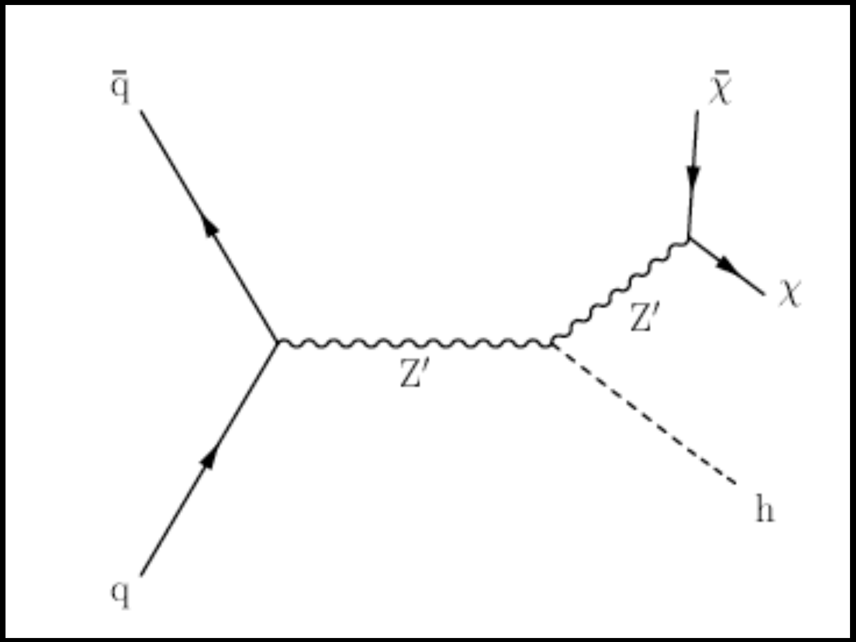
Fixed target experiments

Production/Detection at Colliders

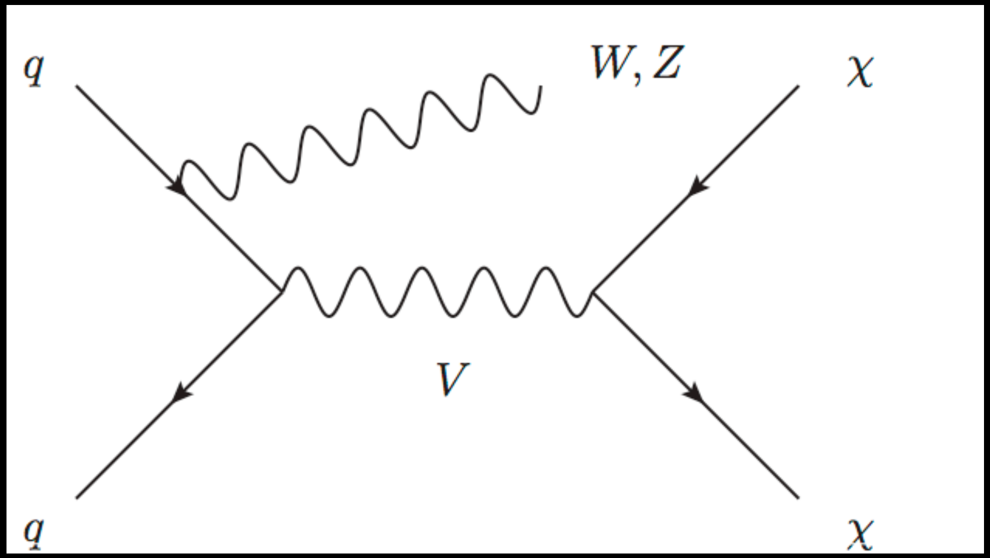
(Remember yesterday's lecture by Prof Charlton)

For center of mass collisions, dark matter can be discovered through Mono-X searches

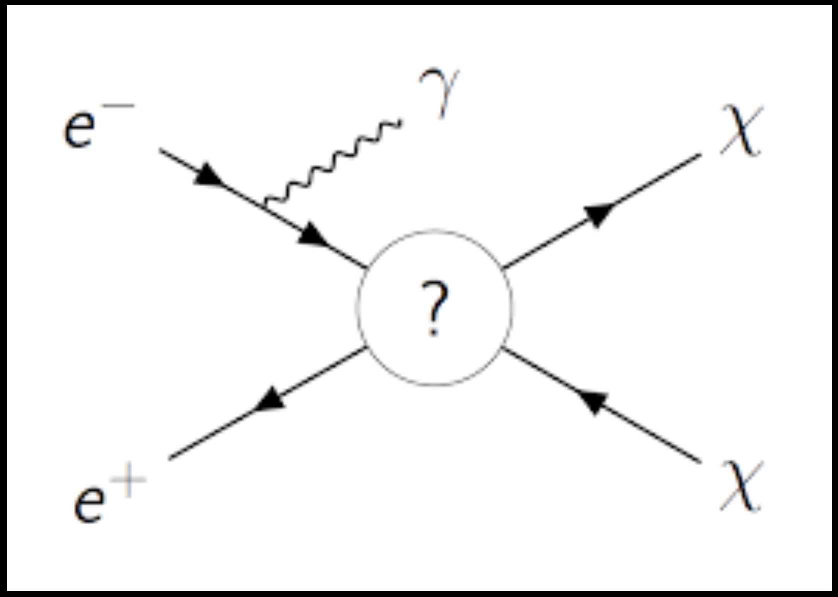
DM is produced and recoils against SM particle, we only see the SM particle. Kinematics allows us to determine DM mass and coupling strength



E.g. mono-Higgs searches at P-P colliders like LHC



mono-W/Z searches at P-P colliders like LHC



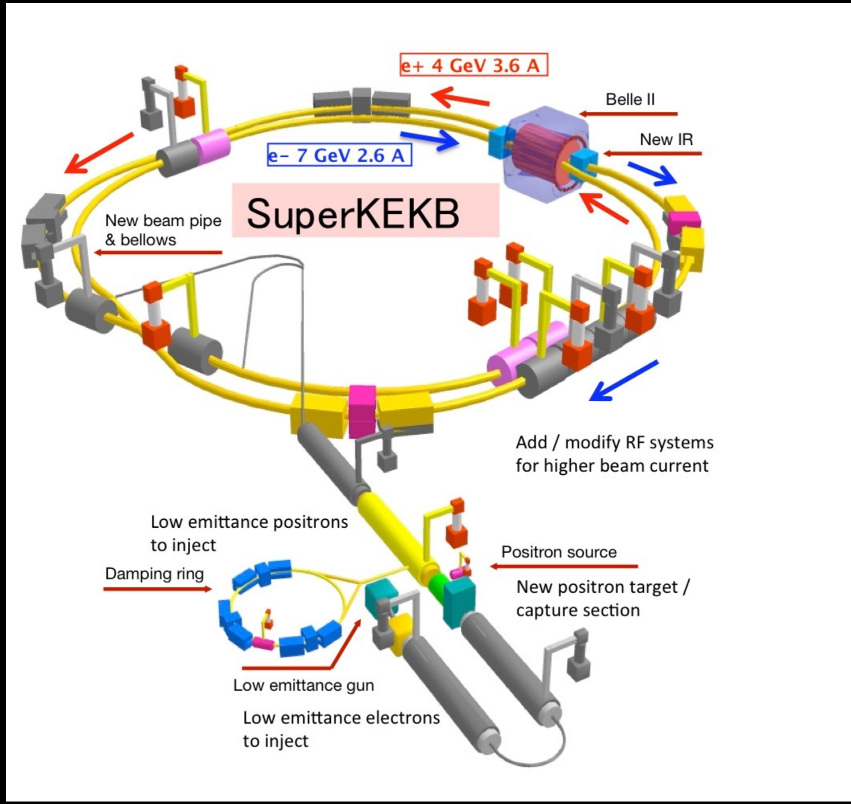
mono-photon searches at e^+/e^- colliders

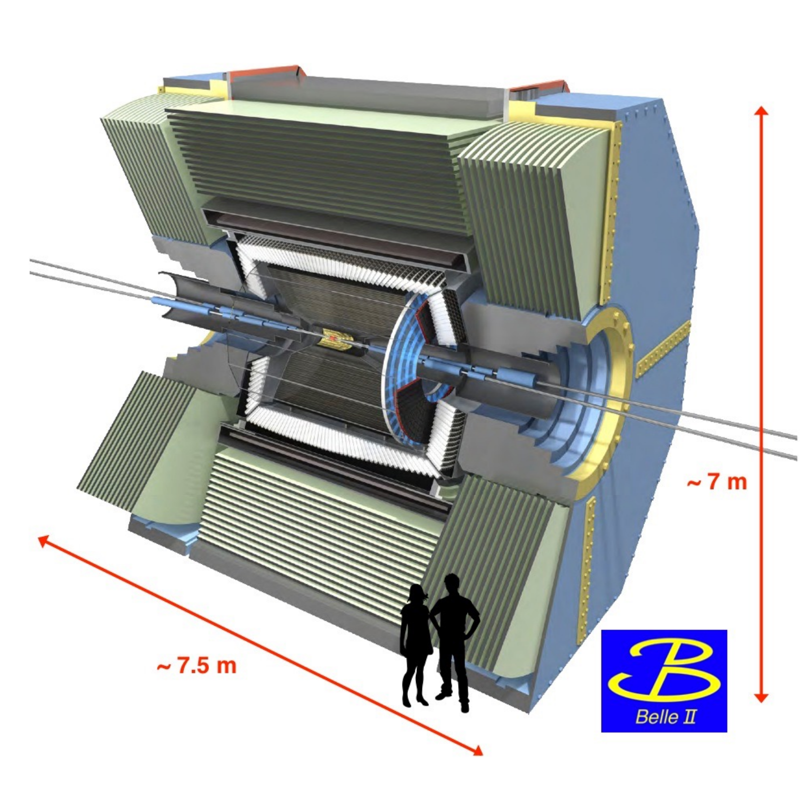
Large Hadron Collider at CERN

14 TeV P-P collisions

Higher DM masses

Belle II Collider at KEK in Japan



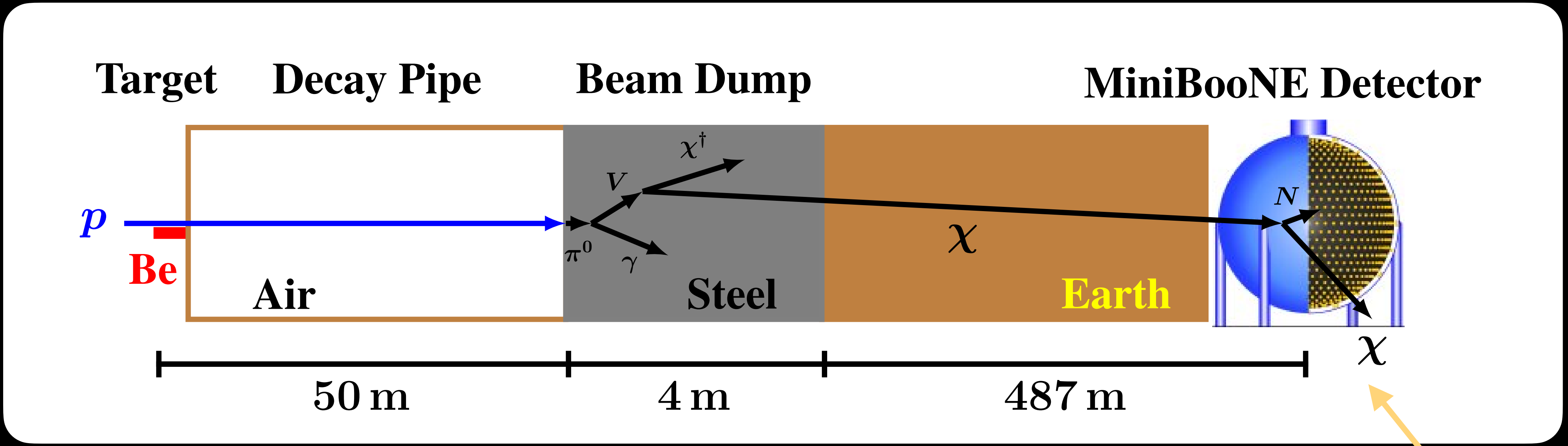


10 GeV e^+/e^- collisions

Probe low DM masses

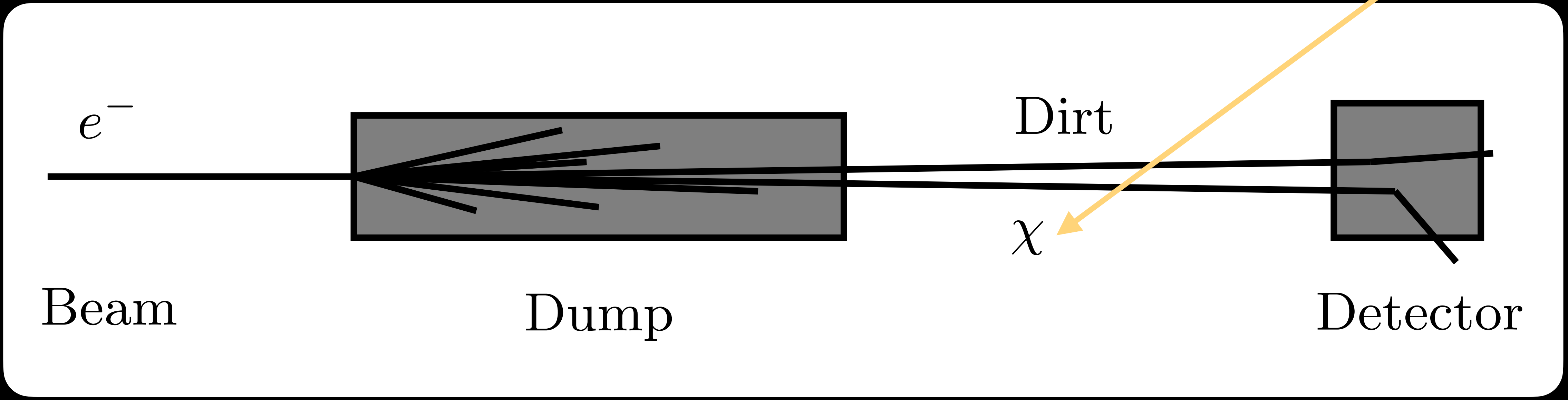
Production/Detection at Fixed target experiments

Proton fixed target experiments



Electron fixed target experiments

Dark Matter



Search for low mass dark matter

Direct Detection

Milky way is surrounded by ‘spherical’ halo of DM

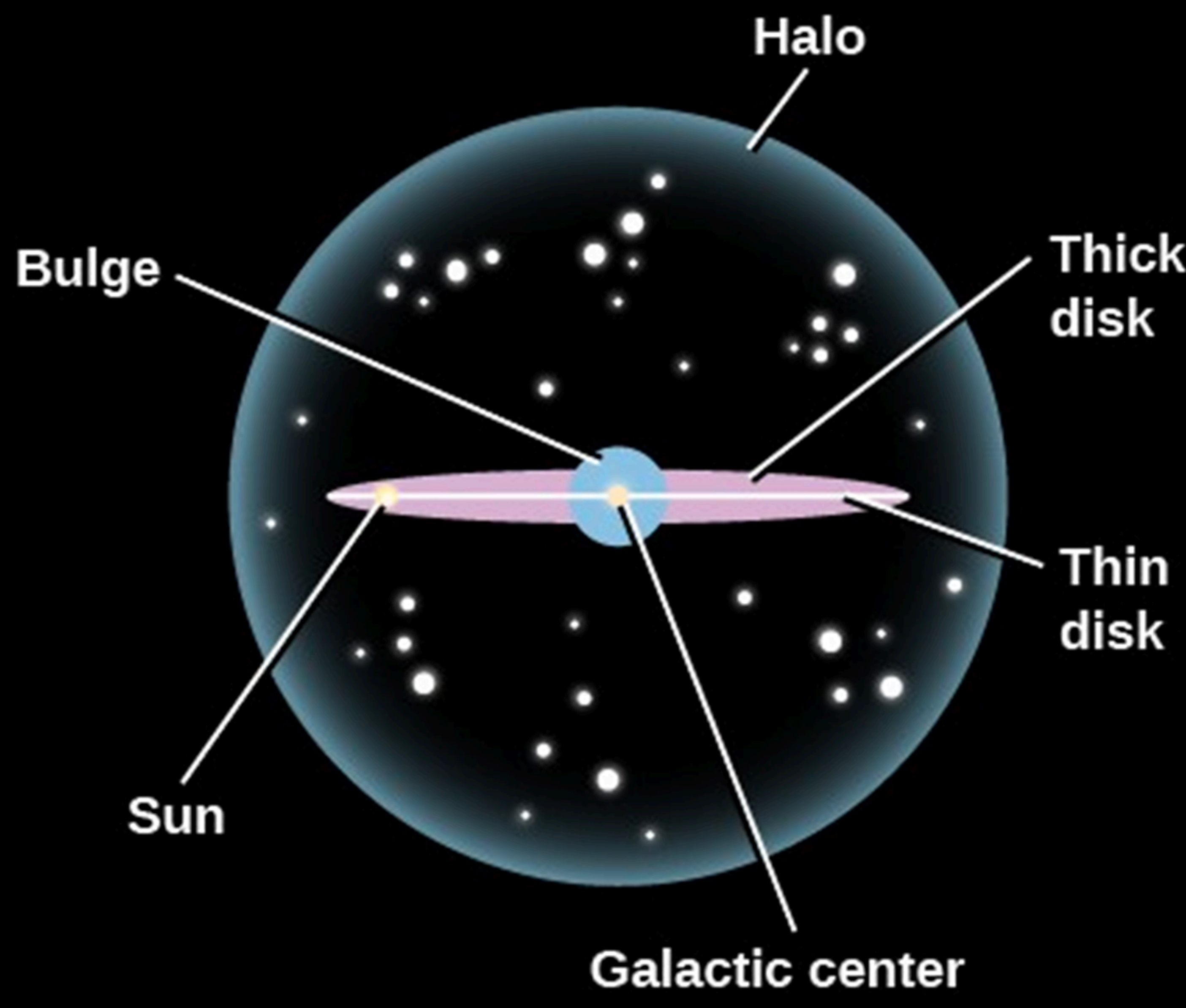


Image: evolution.calpoly.edu

Direct Detection

As sun moves around galaxy, solar system gets hit by dark matter wind

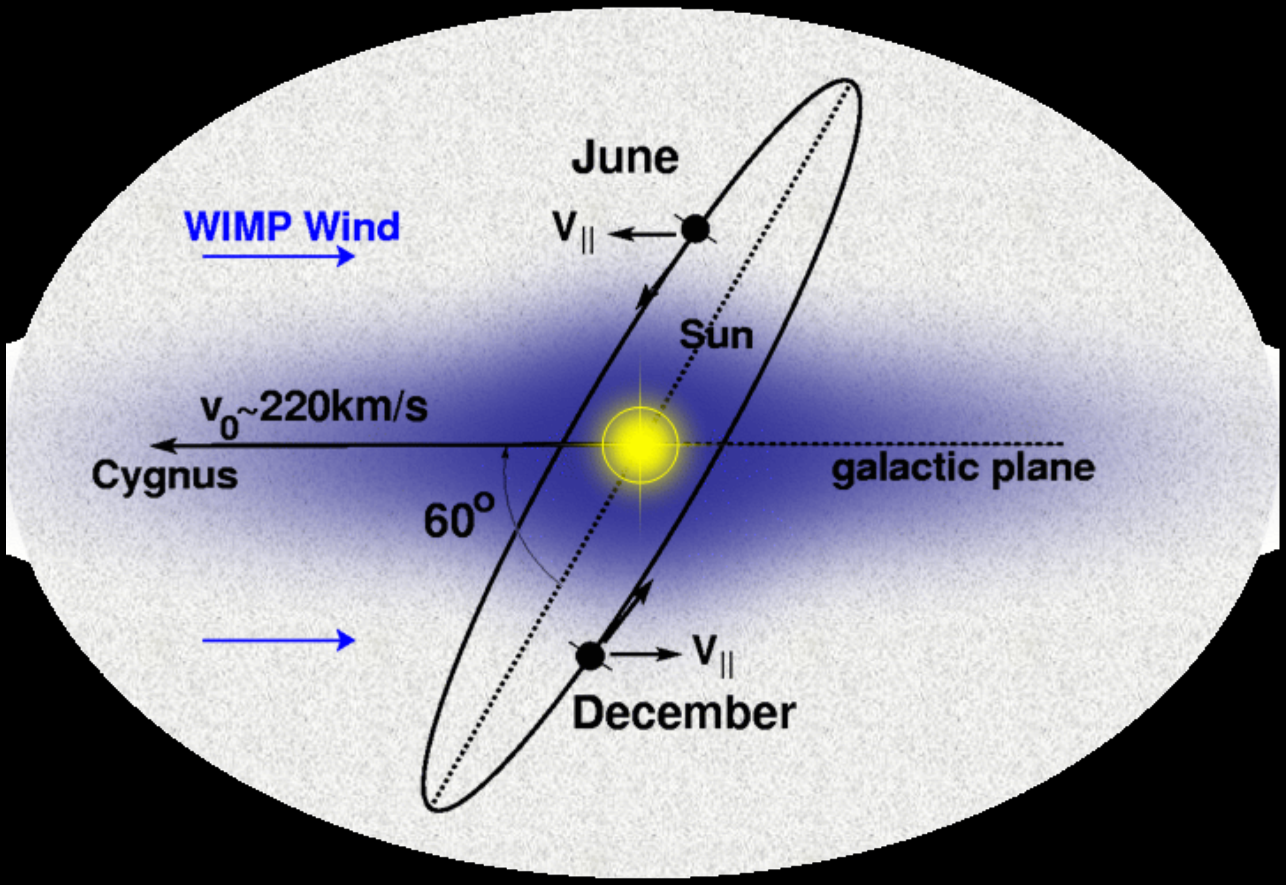


Image: quantumdiaries.org

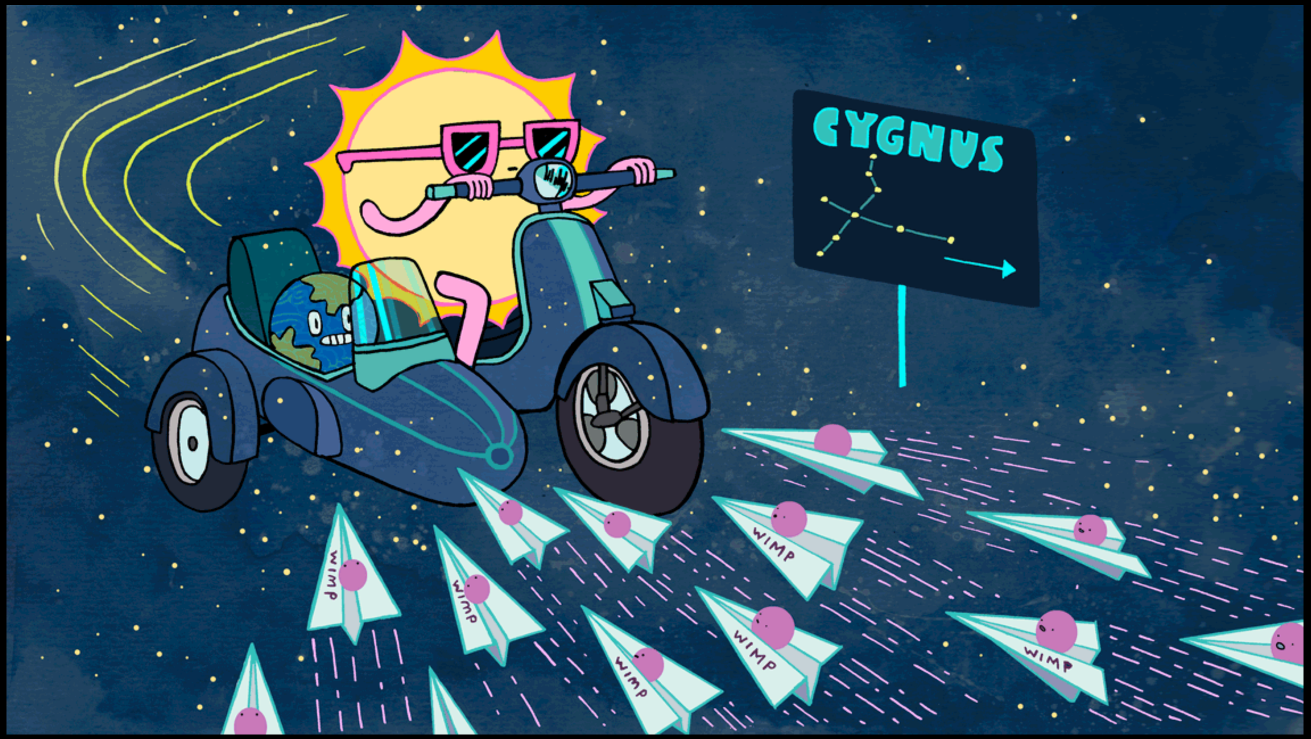


Image: symmetrymagazine.org

Build a detector in a quiet place and patiently wait for dark matter to come knocking

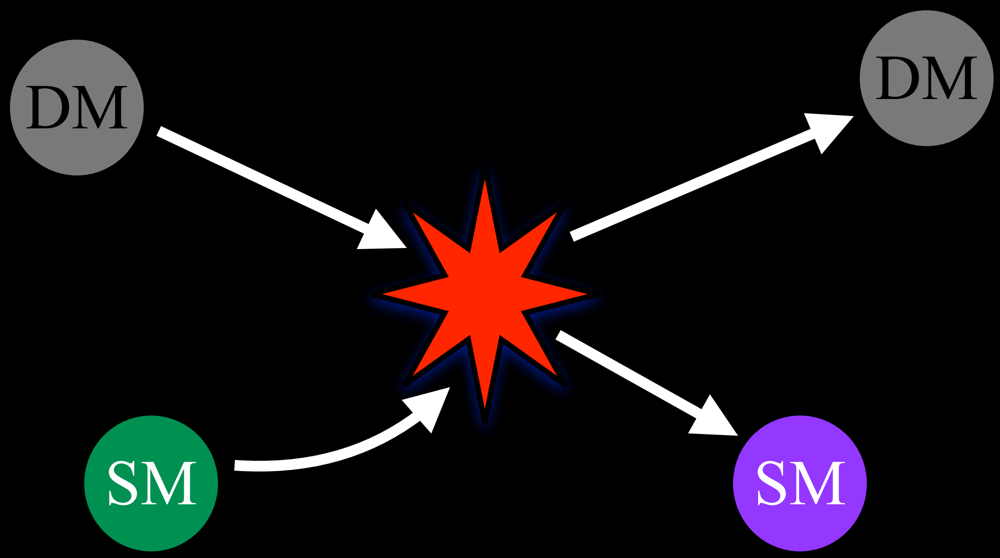
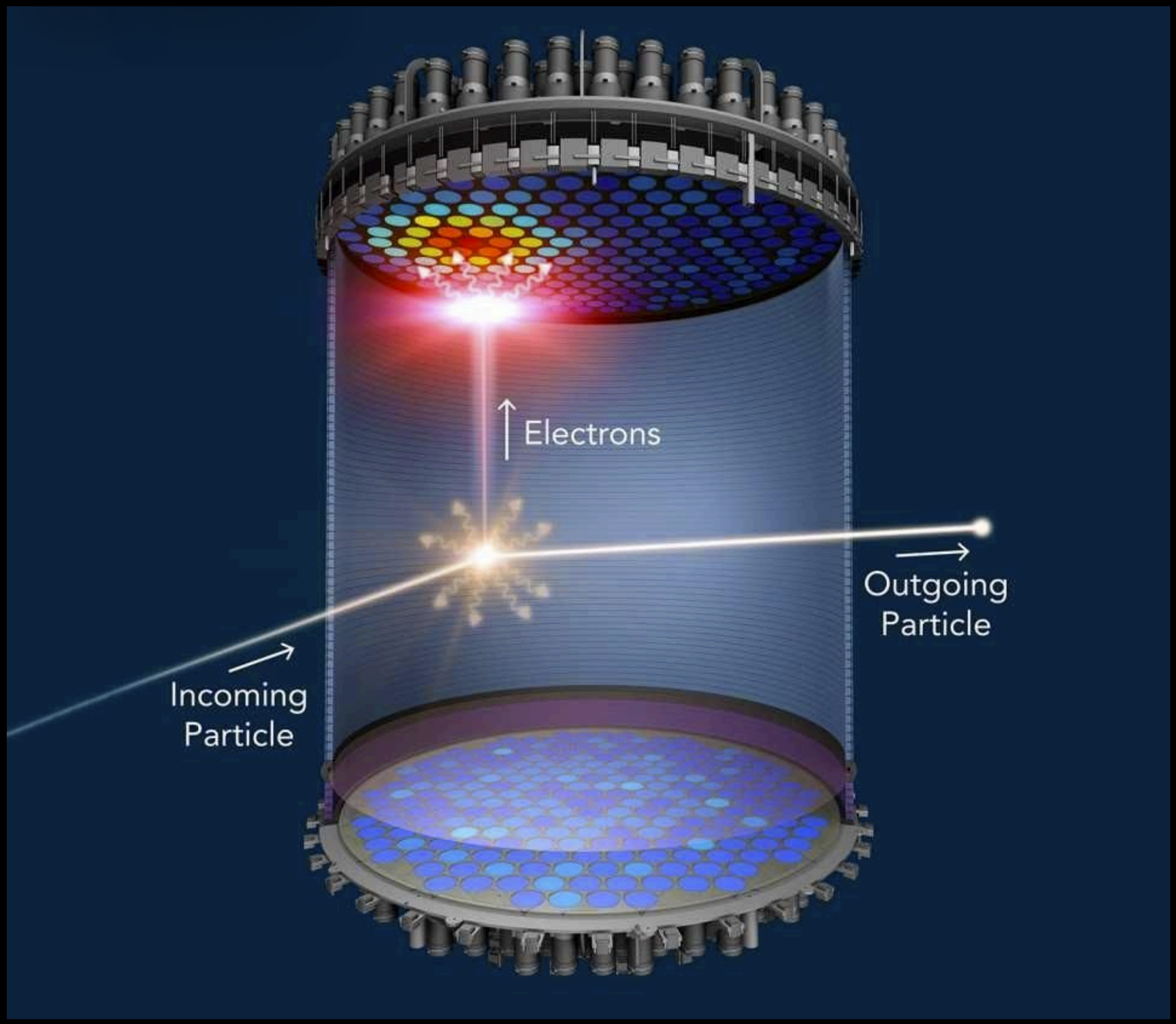


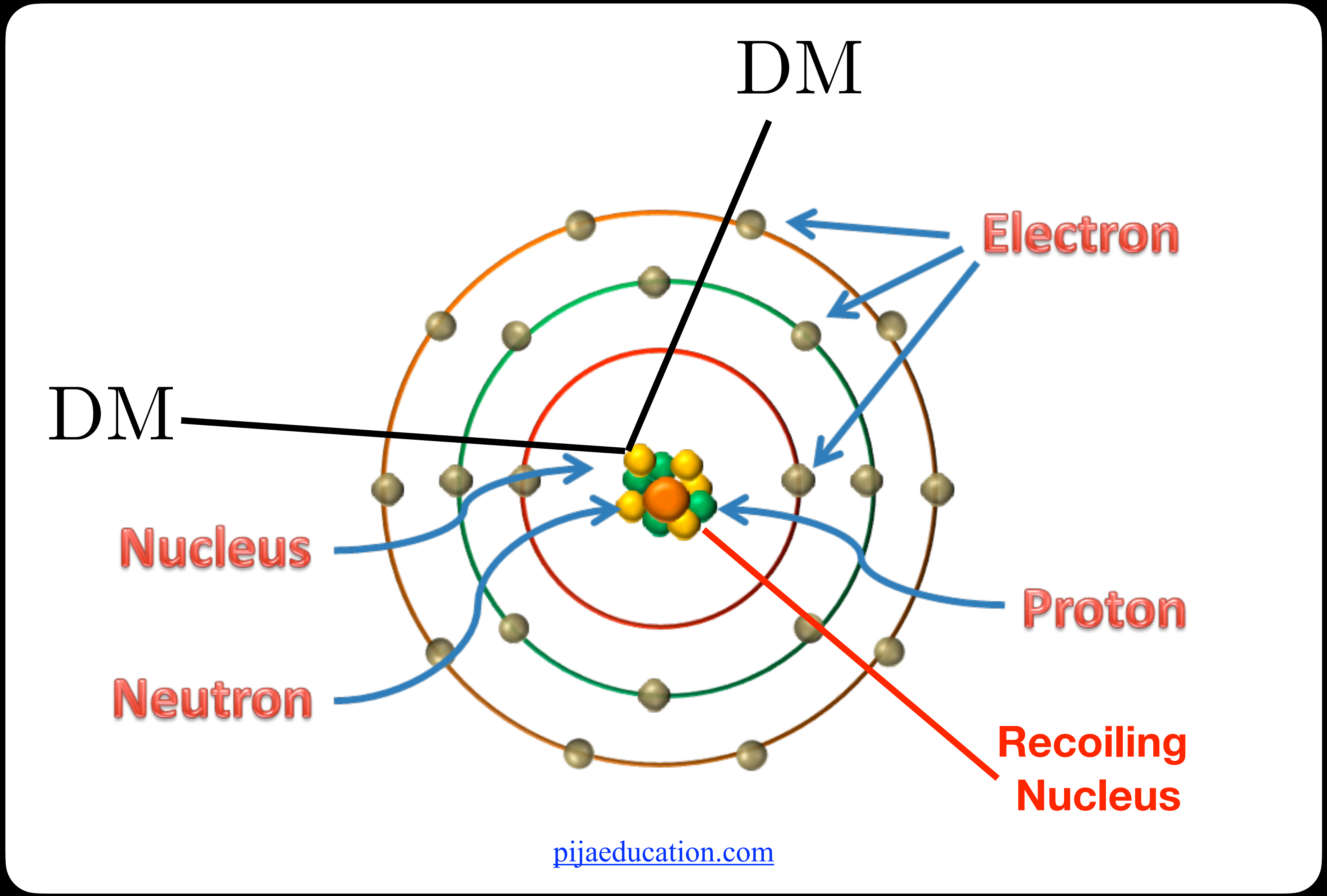
Image: forbes.com



Dark matter hits a nucleus causing a recoil

recoil nucleus is detected and kinematic information used to get dark matter properties

Nuclear Scattering



Nuclear
recoil
rate

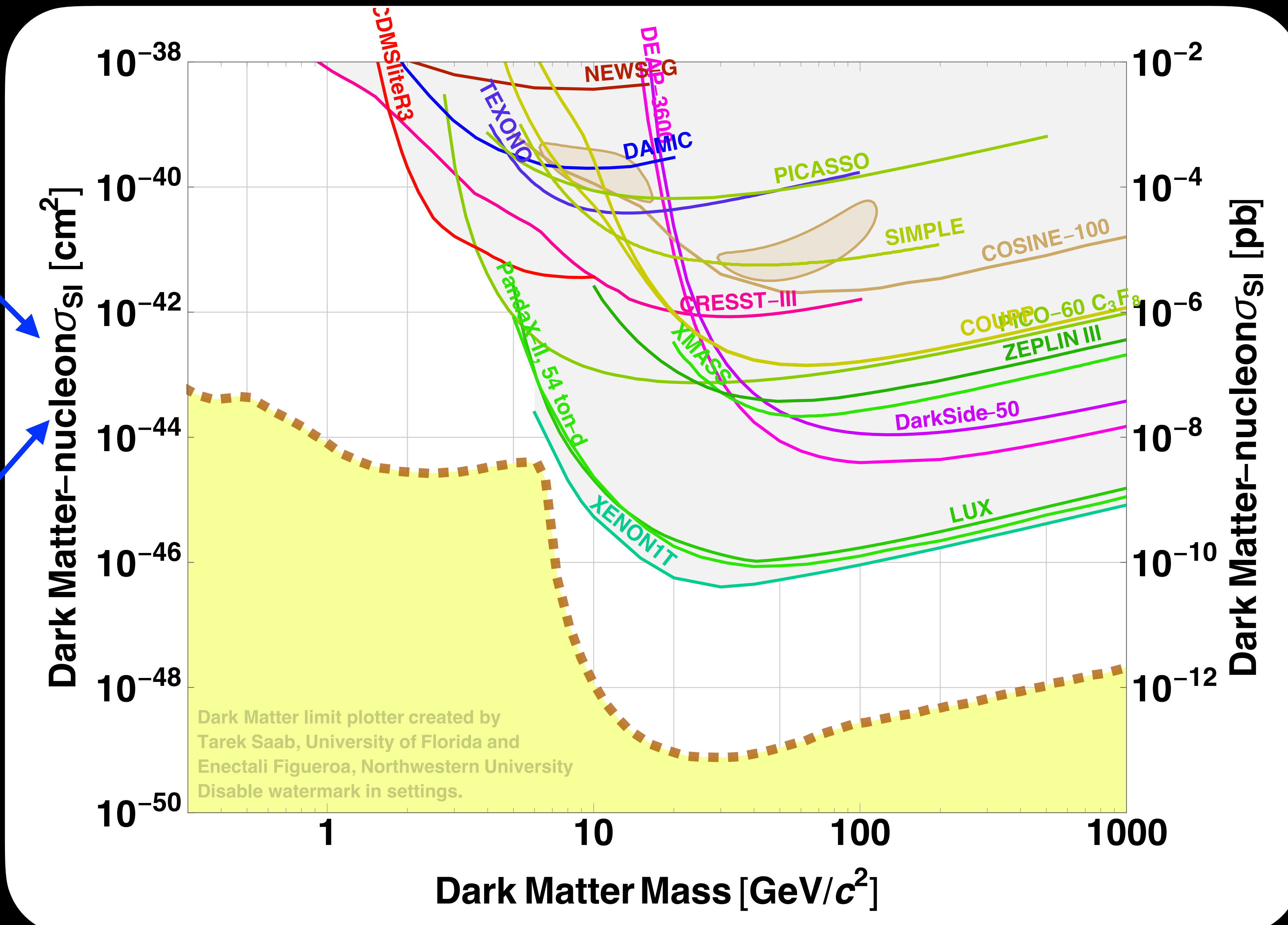
$$\frac{dR}{dE_R} \sim N_T \Delta T \frac{\sigma_{\chi N}}{2\mu^2} |F(E_R)|^2 \frac{\rho_\chi}{m_\chi} \int_{v_{min}}^{\text{inf}} \frac{f(v)}{v} dv$$

Fit recoil rate to experimental data to understand DM parameter space

$$\frac{dR}{dE_R} \sim N_T \Delta T \frac{\sigma_{\chi N}}{2\mu^2} |F(E_R)|^2 \frac{\rho_\chi}{m_\chi} \int_{v_{min}}^{\text{inf}} \frac{f(v)}{v} dv$$

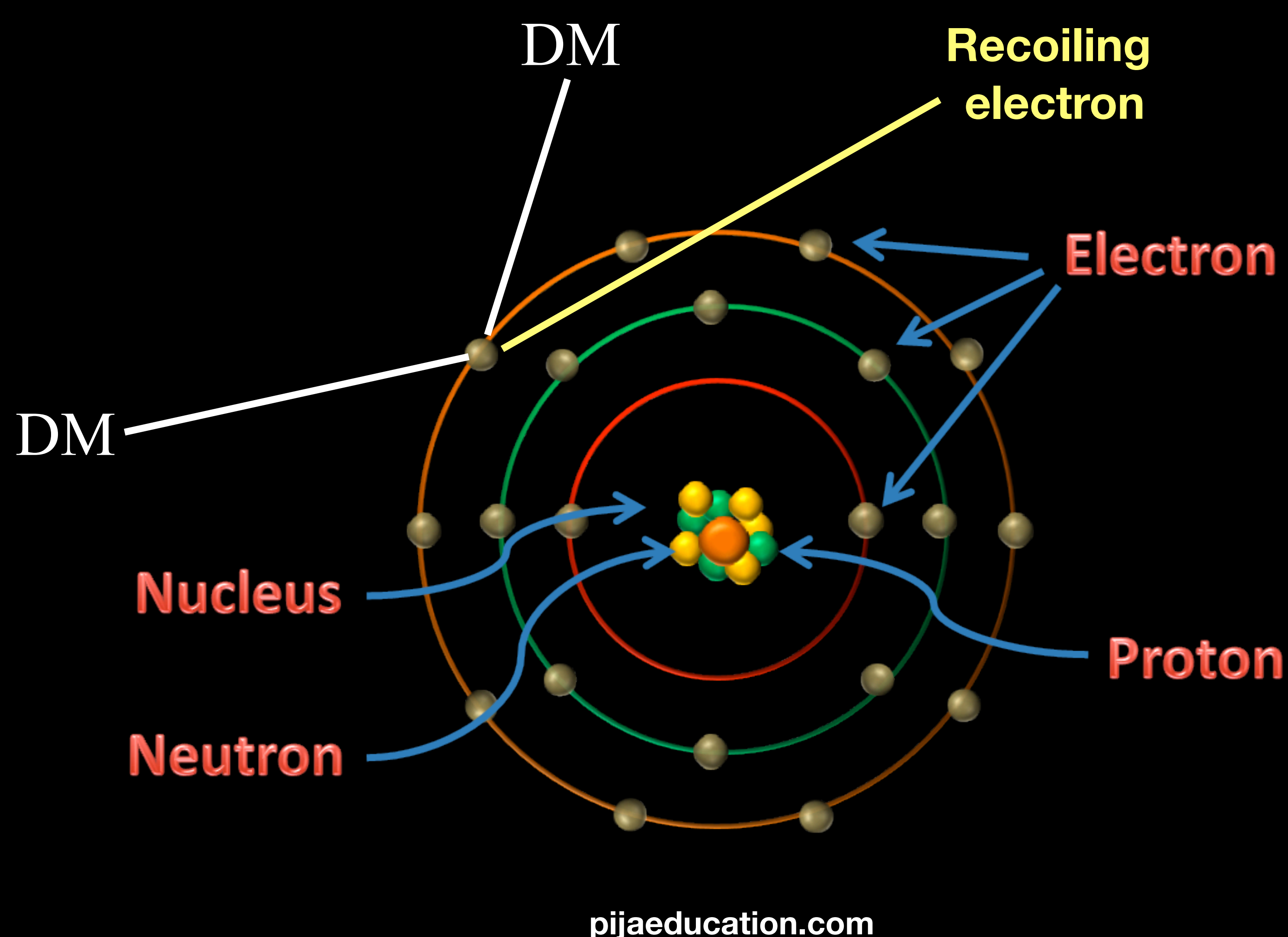
DM-nucleus interaction strength

Particle physics models enter here



supercdms.slac.stanford.edu/dark-matter-limit-plotter

Electron Scattering



Electron recoil rate

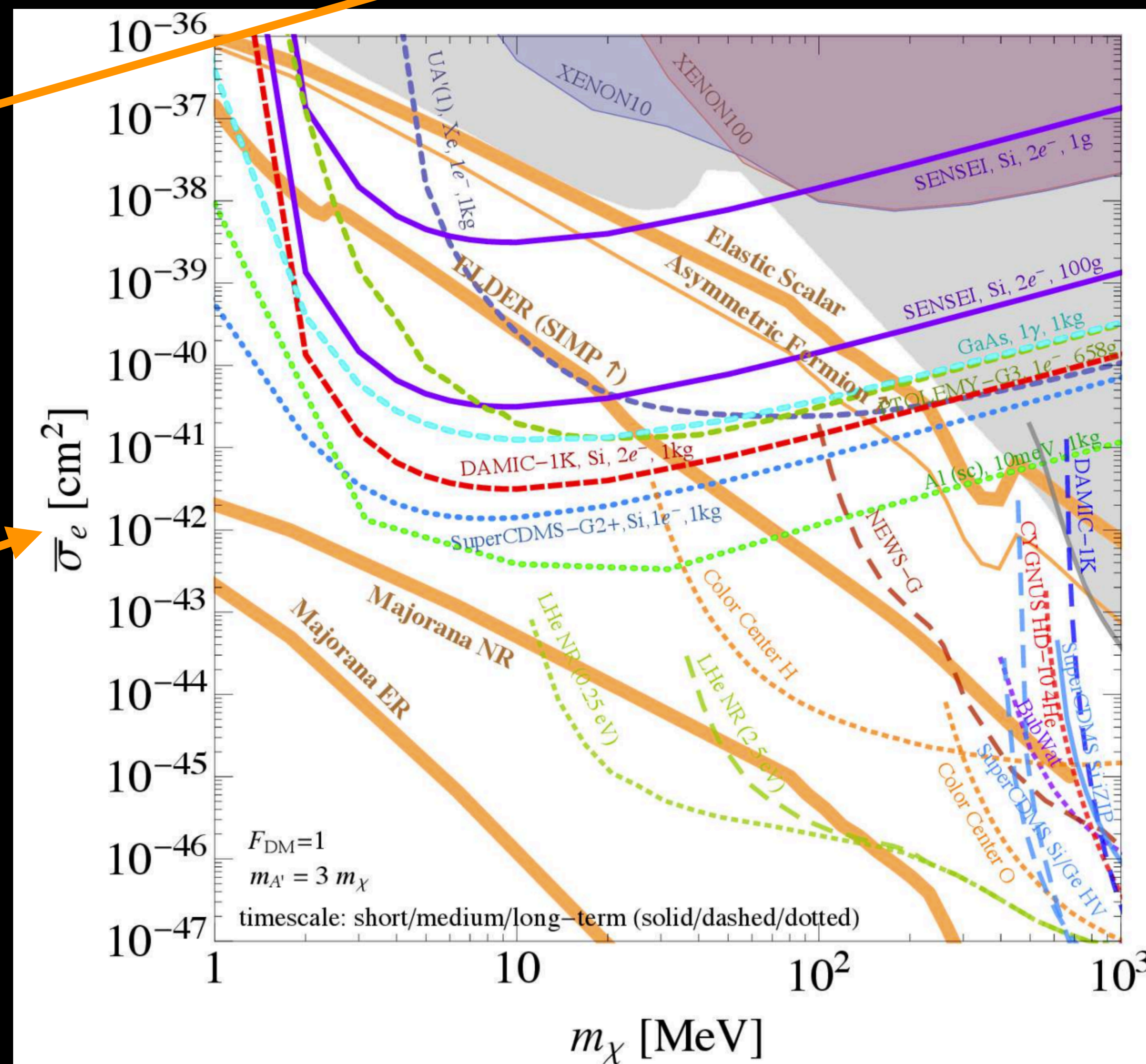
$$\frac{dR}{dlnE_R} \sim N_T \Delta T \frac{\rho_\chi}{m_\chi} \frac{\bar{\sigma}_e}{8\mu^2} \int qdq |f_{ion}^{nl}|^2 |F_{DM}(q)|^2 \int_{v_{min}}^{\mathrm{inf}} \frac{f(v)}{v} dv$$

Fit electron recoil rate to experimental data to understand DM parameter space

$$\frac{dR}{dlnE_R} \sim N_T \Delta T \frac{\rho_\chi}{m_\chi} \frac{\bar{\sigma}_e}{8\mu^2} \int q dq |f_{ion}^{nl}|^2 |F_{DM}(q)|^2 \int_{v_{min}}^{\inf} \frac{f(v)}{v} dv$$

Particle physics information enters here

DM - electron interaction strength



US Cosmic Visions Report: **arXiv:1707.04591**

Example Dark Matter Studies

In 2019 I published a paper where I studied Inelastic dark matter at fixed target & collider experiments

PHYSICAL REVIEW D **99,** 115001 (2019)

Revisiting the dark photon explanation of the muon anomalous magnetic moment

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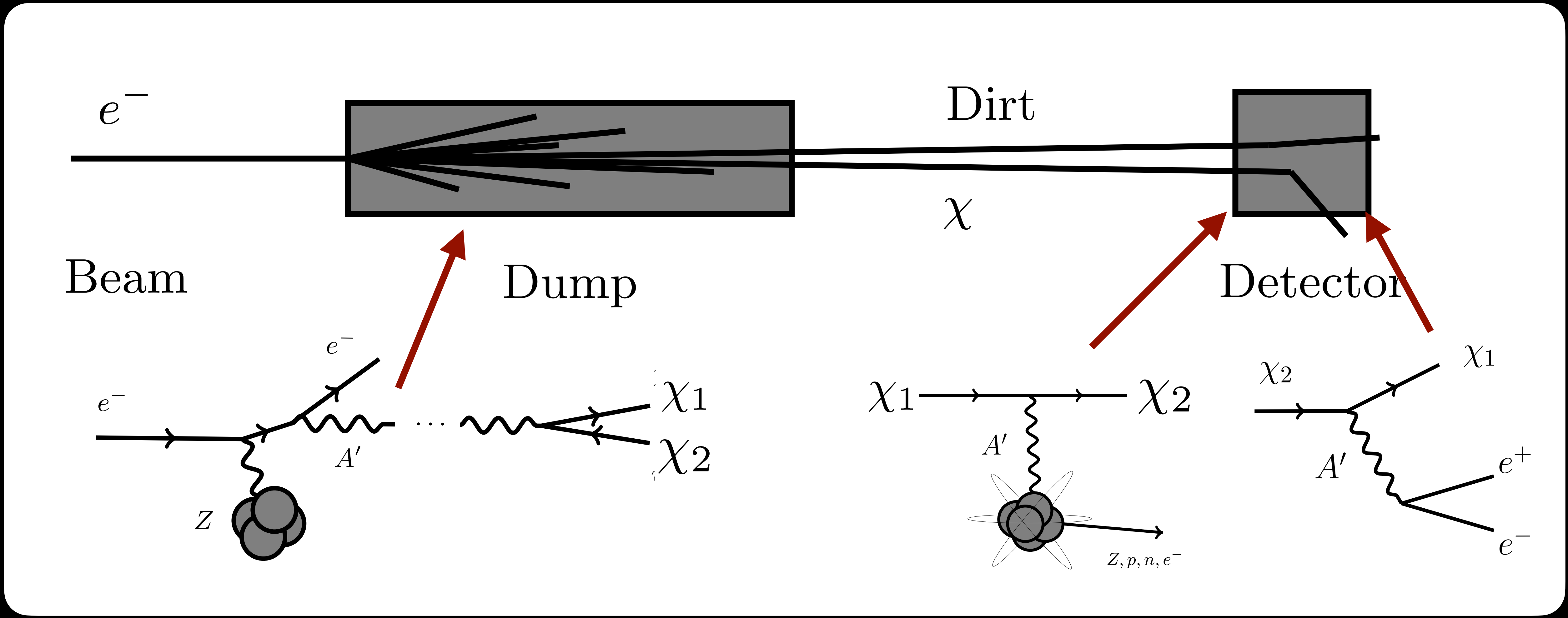
(Received 13 March 2019; published 3 June 2019)

A massive $U(1)'$ gauge boson known as a "dark photon" or A', has long been proposed as a potential explanation for the discrepancy observed between the experimental measurement and theoretical determination of the anomalous magnetic moment of the muon $(g_\mu - 2)$ anomaly. Recently, experimental results have excluded this possibility for a dark photon exhibiting exclusively visible or invisible decays. In this work, we revisit this idea and consider a model where A' couples inelastically to dark matter and an excited dark sector state, leading to a more exotic decay topology we refer to as a semivisible decay. We show that for large mass splittings between the dark sector states this decay mode is enhanced, weakening the previous invisibly decaying dark photon bounds. As a consequence, A' resolves the $g_\mu - 2$ anomaly in a region of parameter

DM is accompanied by heavier dark sector particle

Dark sector connected to SM via new force carrier called dark photon

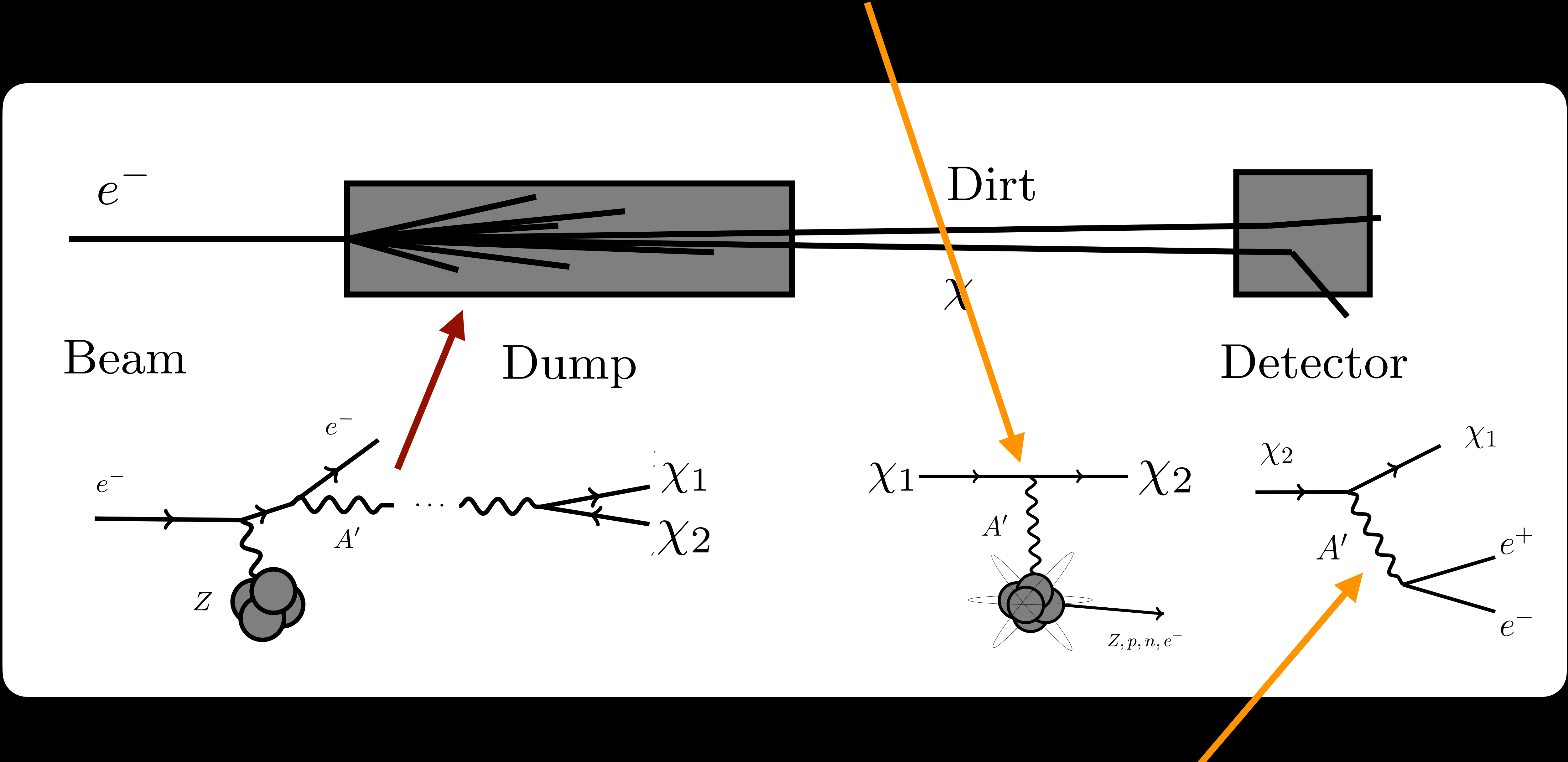
Dark photon is produced in proton & electron fixed target experiments and decays to inelastic dark matter inside experiment



Dark photon is produced in fixed target experiments and decays to inelastic dark matter inside experiment

DM and heavier dark sector state travel to detector

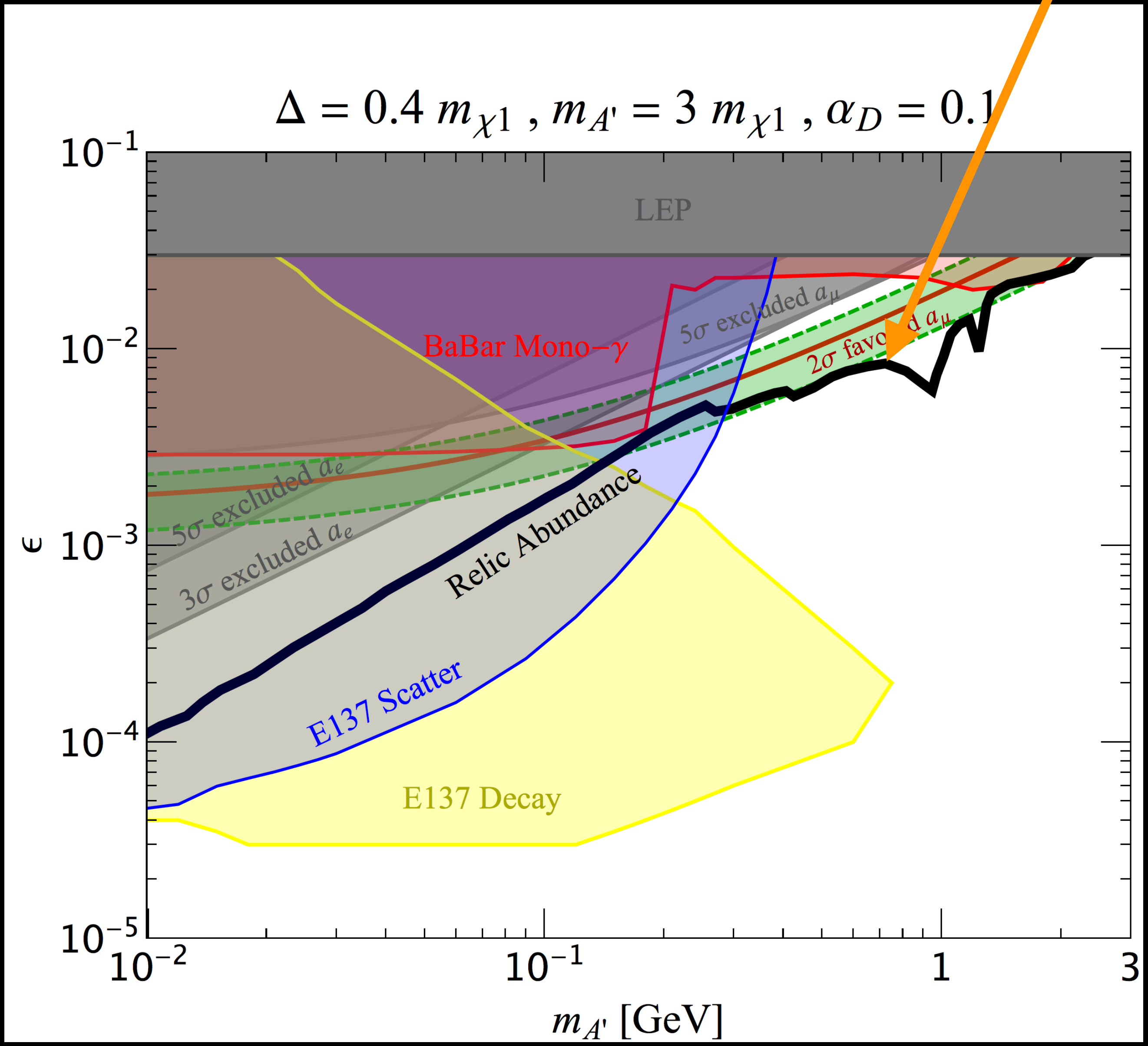
- DM can scatter with SM inside detector

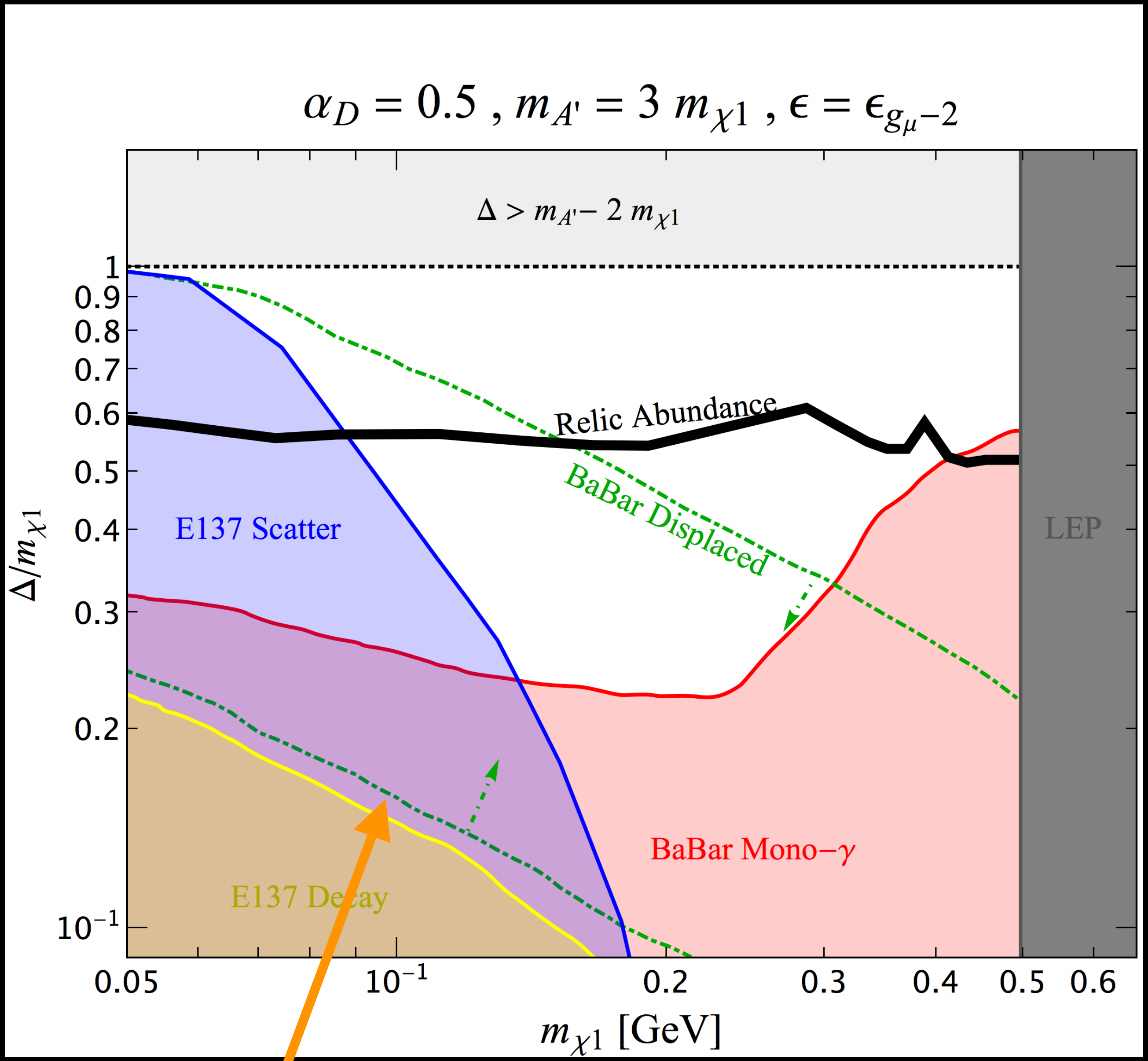


- heavy state can decay to DM and SM particles inside detector

Experimental constraints on this model

Relic density calculation compared to data





Theory computations compared to accelerator experiment data

Follow-up work

Calculated quantum corrections on the light dark matter relic density process

Radiative Corrections to Light Thermal Pseudo-Dirac Dark Matter

Gopolang Mohlabeng,[1,2,*] Adreja Mondol,[1,†] and Tim M.P. Tait[1,‡]

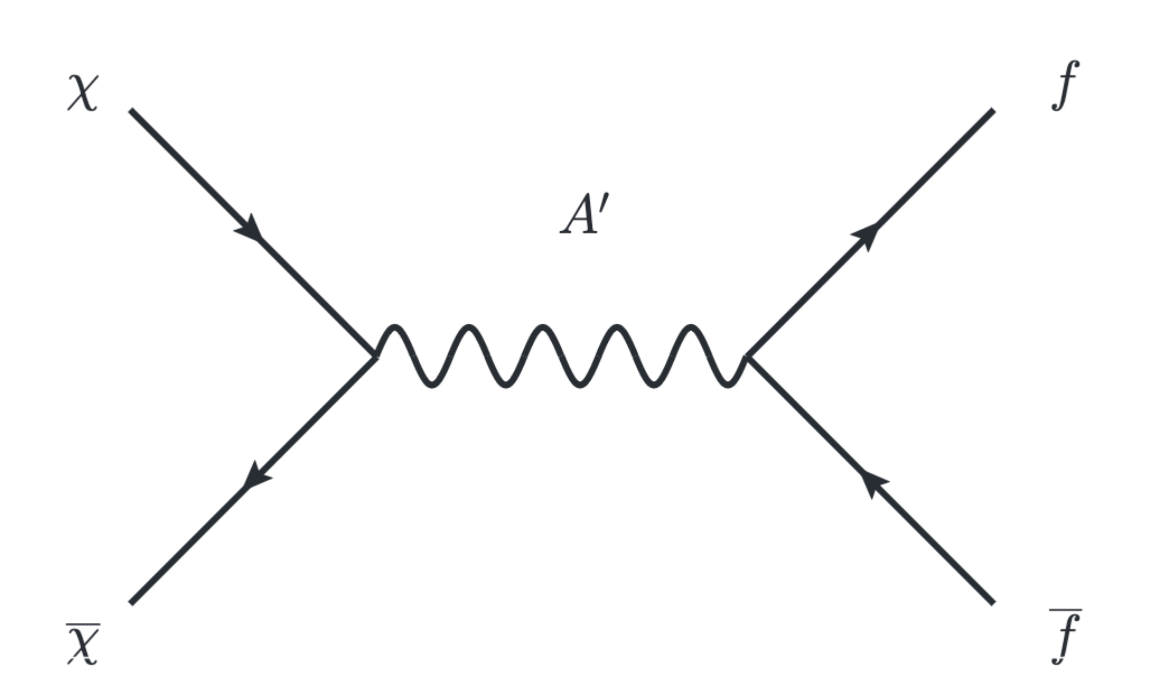
[1] *Department of Physics and Astronomy, University of California, Irvine, CA 92697, USA*
[2] *Department of Physics, Simon Fraser University, Burnaby, BC, V5A 1S6, Canada*
(Dated: May 16, 2024)

Light thermal dark matter has emerged as an attractive theoretical possibility and a promising target for discovery at experiments in the near future. Such scenarios generically invoke mediators with very small couplings to the Standard Model, but moderately strong couplings within the dark sector, calling into question theoretical estimates based on the lowest order of perturbation theory. As an example, we focus on a scenario in which (pseudo)-Dirac fermion dark matter is connected to the standard model via a dark photon charged under a new $U(1)'$ extension of the standard model, and we investigate the impact of the next-to-leading order corrections to annihilation and scattering. We find that radiative corrections can significantly impact model predictions for the relic density and scattering cross-section, depending on the strength of the dark sector coupling and ratio of the dark matter to mediator mass. We also show why factorization into the yield parameter Y typically presented in literature leads to imprecision. Our results are necessary to accurately map experimental searches into the model parameter space and assess their ability to reach thermal production targets.

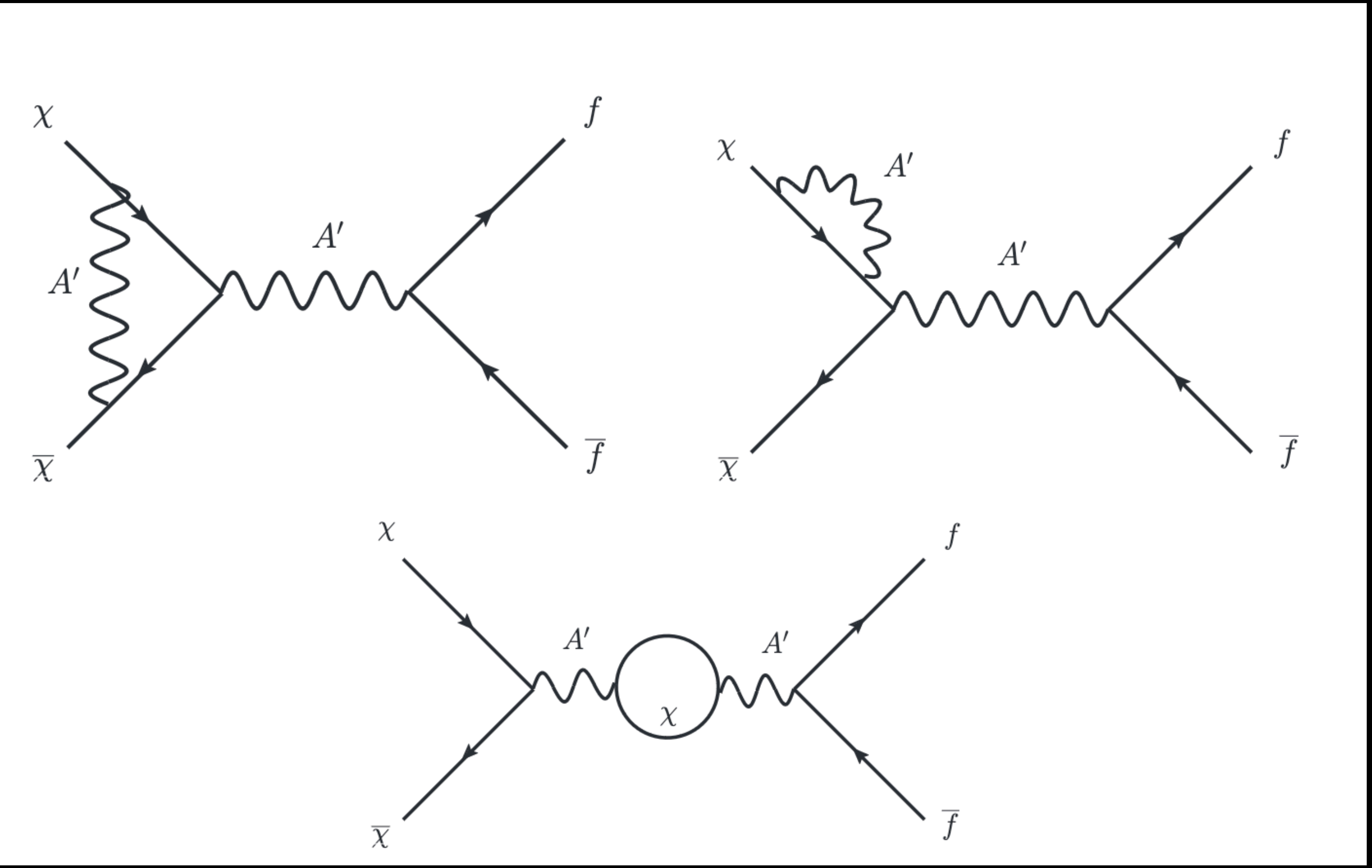
Understand how these corrections impact the relic density

Quantum corrections on dark matter relic density

Leading diagram

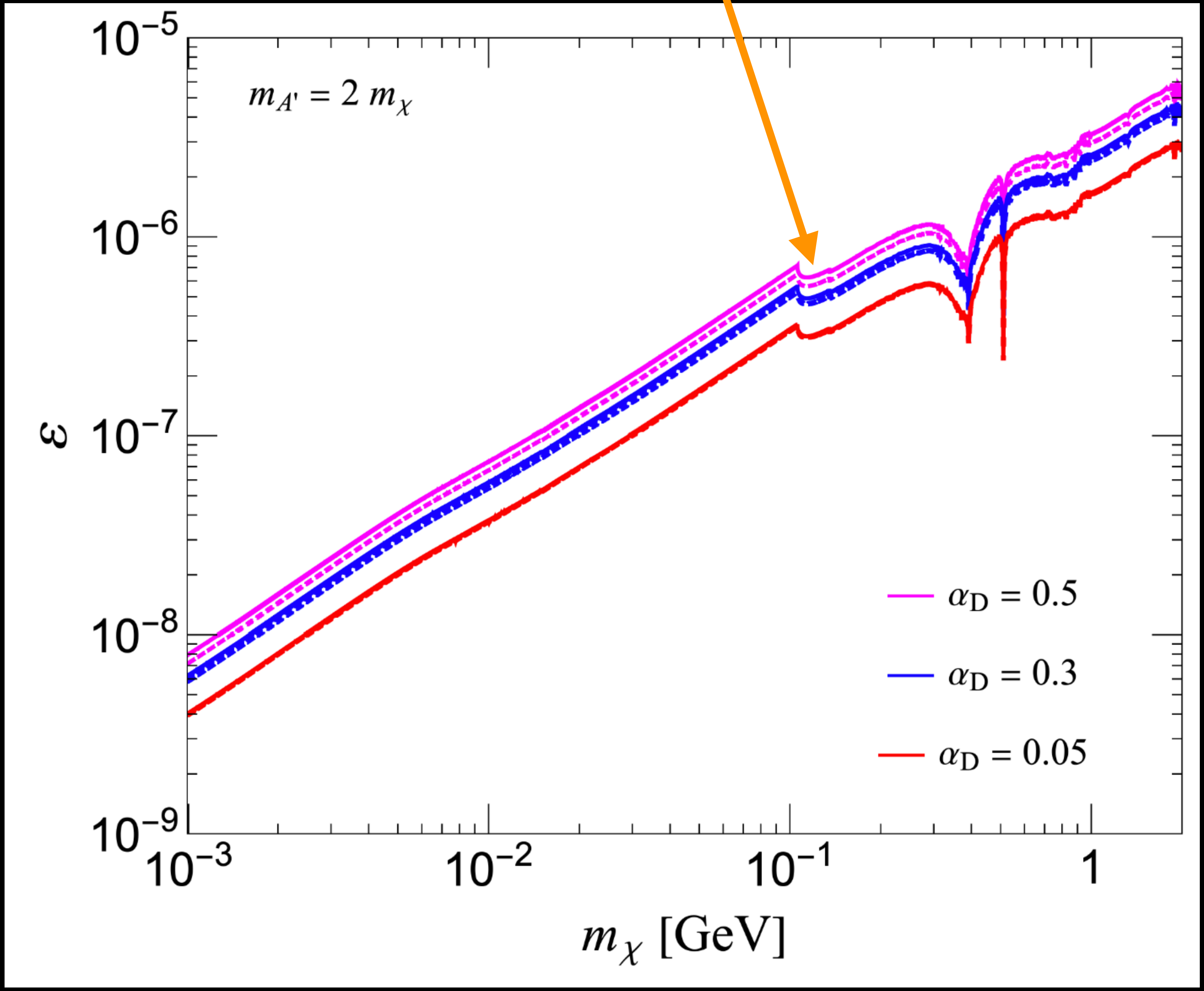


Quantum corrections



Quantum corrections on dark matter relic density

Relic density calculation compared to data



Small changes from quantum corrections to the dark matter process

Recap: lecture 2

- Cosmological abundance and production of dark matter

- Calculation and Understanding of Relic density from Freeze-out

- Methods of detecting dark matter

Indirect detection

Production at colliders/Accelerators

Dark matter direct detection

- Example light dark matter models

Questions?

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